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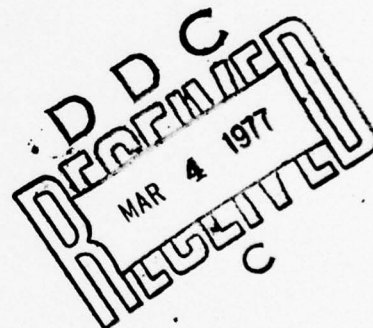## Distribution and Movement of Cyclonic Gulf Stream Rings

Technical Report

Ref. No. 77-1

by

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and

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Approved for Distribution _____

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ABSTRACT

A study of the general distribution and movement of cyclonic
Gulf Stream rings was made by analysing 50,000 temperature records
obtained from the National Oceanographic Data Center and Fleet Numeri-
cal Weather Central. The data were taken from 1970 through 1973 in
the region bounded by 20-40°N and 50-80°W. Additional ring observa-
tions from other sources were also used. Twelve ring time-series,
together with fifteen single ring observations were obtained; approxi-
mately eleven rings were found to exist at one time. They typically
moved westward, turned southwest when close to the Gulf Stream and
appeared to coalesce with the Stream near Florida. On the average,
about one and a half rings a year moved down this path, with a mean
speed of three km a day and an estimated life span of two to three
years. Although rings were concentrated in the northwestern Sargasso
Sea, a few were found east of 60°W. However, the low data density in
the eastern region prevented detailed analysis there. Several warm
eddies, with at least a 150-meter deepening of the main thermocline,
were also found.

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PREFACE

This report in a slightly different form was submitted by David
Lai as partial fulfillment of a Master of Science degree in Oceanography
at the University of Rhode Island (Lai, 1976). Recent data (1974-76)
has been added in order to extend the initial results (see Appendix H).

Data was obtained from a series of R/V Trident cruises (TR-98,
104, 125, 128, 161, 168, 175), as well as from other sources, NODC,
FNWC, NAVOCEANO. We thank all those who generously made their ring
observations available to us, especially R. Cheney, G. Gotthardt, and
R. Pershal of NAVOCEANO.

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I. INTRODUCTION

Despite considerable effort spent studying Gulf Stream rings, their movement, geographical distribution and the number that exist at a time remains largely unknown. This is due to the difficulty and the large cost in following rings by ship and aircraft and the lack of remote techniques to track them over time. The problem being addressed in this study was to use all data sources: satellite infrared photographs, bathythermographs (XBT's) and hydrostations, in an attempt to reveal the general distribution and movement of rings.

Gulf Stream rings are formed east of Cape Hatteras from pinched off meanders of the Gulf Stream (Figure 1). Although they are formed on either side of the Stream, this study concerns those on the southern side. They consist of a cooler, fresher core of Slope Water (Iselin, 1936) embedded in a swift ring of counterclockwise current, and hence, are called cold or cyclonic rings (Figure 2). Cyclonic rings are large scale features with an overall diameter of 200 to 300 km and a depth of several km (Fuglister, 1972). They appear to be the most energetic eddies in the ocean and are integral and vital parts of the Gulf Stream System. They are responsible for part of the recirculation of the Gulf Stream water via their formation, movement and their final coalescence with the Stream. They are thought to play an important role in the transfer of energy from the Gulf Stream to the midocean areas as transient eddies and in redistributing low frequency mesoscale energy, momentum, chemicals and even biota in the ocean. Hence, the study of

rings is important not only to the understanding of the Gulf Stream System, but also the dynamics of the midocean regions.

Cyclonic rings were first discovered by Iselin (1940) studying long-term variations of the Gulf Stream transport. Fuglister and Worthington (1951) observed the actual formation of a ring in a Multiple Ship Survey. Since then, there have been several reports on different types of ring movement. Fuglister (1972) observed two rings for five months during which time they moved in a looping, clockwise trajectory with a speed of about 10 cm/sec; their mean movement was slightly south of westward with a speed of 7 cm/sec. Richardson, Strong and Knauss (1973) reported the southwest motion of a ring for fourteen months and its apparent coalescence with the Stream near Florida. A westward moving ring was remotely tracked by SOFAR floats for four months (Cheney, et al., 1976). Further remote tracking of rings is being done by the use of satellite-tracked surface buoys.

Although the number of rings formed each year is unknown, a few estimates have been made. Newton (1961) estimated that five to seven cyclonic rings might form each year and Fuglister (1972) suggested the number to be five to eight by a different model. Parker (1971) was able to identify 62 rings in the western Sargasso Sea, using the Woods Hole Oceanographic Institution bathythermograph data file from 1932 to 1970. However, it is very likely that some of these 62 rings are different observations of the same rings. Hence, the question of the distribution and movement of rings remains unresolved.

II. DATA ACQUISITION

Nearly 50,000 temperature records taken during 1970-73 in the region bounded by 20-40°N and 50-80°W were obtained from the Navy Fleet Numerical Weather Central and the National Oceanographic Data Center (hereafter refered to as FNWC and NODC respectively). The records are unevenly distributed and are concentrated heavily in the Gulf Stream and the western Sargasso Sea (Figure 3). There is an abrupt decrease in the number of data in the eastern region. There are also some apparent erroneous data which appear on land.

The data are mostly expendable bathythermographs (XBT's), together with a few salinity-temperature-depth stations (STD's) and hydrostations (Table 1), reaching various depths (Figure 4). They were taken from a variety of ships including oceanographic, Navy, merchant and fishing vessels. Unfortunately most of the XBT's from the U.S. Naval Oceanographic Office cruises, which contain numerous ring observations, have not been submitted to NODC and were not analysed in this study. However, a summary of their results has been published in the Gulf Stream Monthly Summary (1970-73) and these observations were added to this study. Other ring observations reported by other available sources which did not appear in the above data file (Richardson, Strong and Knauss, 1973; Stumpf, Strong and Pritchard, 1973; Raschig, 1973; Gotthardt, 1973), including satellite infrared photographs, were also added.

III. METHOD OF ANALYSIS

Analysis consisted of computing the mean temperature field at five different depths. Anomalies from the mean, equivalent to a 150 m upward displacement of the isotherms, were identified. A "ring observation" was defined to consist of at least three anomalies identified within a five day period and within a diameter of 100 km. Since the identification of rings depends strongly on what is considered as an anomaly, the mean temperature field and ring criteria are carefully described below.

Although the change in the depth of isotherms was used for identifying anomalies, maps of isotherm topography were not used because the XBT's with minimum temperatures higher than that of the isotherm under consideration would have been left out in the computation, making such maps cold-biased. Hence, the mean horizontal temperature field at various depths were used instead. Temperature anomalies equivalent to a certain displacement of an isotherm from its mean depth were identified by considering the mean temperature gradient and the difference in the mean temperature field between two depths.

Mean Temperature Field

The region was divided into small bins (1°X1° or 2°X3°, depending on the data density) and the mean temperature at depths of 300, 450, 500, 600 and 700 m in each bin were computed. However, the data distribution is neither random nor normal, often due to the large number of measurements taken in a ring within a short period of time (Figure 5).

This bias is more acute in some bins (Figure 6a,b), resulting in lower mean temperatures and large temperature variances. These cold data were removed from the dataset in order to obtain a more representative mean temperature field. Those which deviated from the preliminary mean temperature by one standard deviation in bins whose root mean square temperature is greater than one degree Centigrade were removed and the mean temperature was recomputed from the remaining data; figure 7 shows the values at a depth of 450 m. Due to the extreme low data density or high percentage of ring data in a few bins, their mean temperatures were obtained by interpolating between adjacent values (see Appendix F).

The temperature contour maps were obtained by linear interpolation between mean temperature of adjacent bins (Figure 8). The mean position of the Gulf Stream is marked by the region of large horizontal temperature gradient and the axis of the mean Gulf Stream coincides with the 13°C isotherm at 300 m. At 300 m, the field is dominated by water between 17.5 to 18°C (the Eighteen Degree Water, Worthington, 1959) which extends south to nearly 20°N. In the deeper layer (700 m), the center of the subtropical gyre can be seen centered near 34°N and 72°W. South and east of this point, the main thermocline rises, indicative of the Gulf Stream recirculation gyre (Worthington, 1977).

A search was made for the seasonal variations in the main thermocline. No seasonal change in temperature at depths greater than 400 m was detectable from noise level which was approximately $\pm$ 50 m. Identification of rings was made using time averaged temperature fields.

Ring Criteria

In general practice and as a convenient standard, the size of a ring is frequently estimated from the extent of the 15°C water at a depth of 500 m (Cheney and Richardson, 1976). Since the depth of the 15° surface lies at about 650 m in the northwestern Sargasso Sea, the edge is equivalent to about 150 m upward displacement of the isotherms from the mean field. The 150 m displacement is about twice the displacement amplitude of the eddies in the MODE area (Draft Synoptic Atlas, 1974). Thus, a 150 m or more upward displacement of the thermocline at 450 m was chosen as an anomaly indicative of a ring. Furthermore, at least three anomalies observed within a five day period within a 100 km of diameter were then considered to consist of a "ring observation". The five day period and 100 km of diameter criteria are based on realistic values of ring movement and size. The criterion of three anomalies was used to reduce the effect of erroneous data (see also Appendix A). The criteria used here are similar to those used by Parker (1971) in his study, using older and shallower mechanical BTs.

The ring criteria were changed in order to see how the results were affected. It was found that although the total number of ring observations varied with changes in time and size criteria (up to two weeks and 200 km respectively), the ring trajectories and the total number of different rings did not vary significantly. However, variations in the criteria of height anomaly did show different results.

When the height criteria was 100 m instead of 150 m, the number of anomalies increased by a factor of three in the southwest region; the increases were smaller in other regions (Table 2). A large number of

the additional anomalies were associated with previously identified rings obtained from the 150 m anomalies, but five new "ring observations" were identified. Attempts to infer ring time-series from the 100 m anomalies proved fruitless because the results depended critically on the subjective decisions as to which anomalies to use and which to disregard. When the height criteria was lowered to a 50 m displacement, even "ring observations" could not be identified without much subjective choosing of anomalies. On the other hand, when an anomaly criterion of more than 150 m was used, most of the measurements taken on ships of opportunity were eliminated since usually they were not taken at or near the center of the rings; it was impossible to infer movement of rings from the few ring observations identified.

Temperature anomalies in the region bounded by 20°N, 50°W, the Gulf Stream and the Antilles Islands were identified and "ring observations" were formed from those which satisfied the ring criteria. The ring observations, together with those anomalies which did not satisfy the ring criteria, were used to trace individual ring movement. One thousand and eight temperature records, 6% of all the data, were identified as cold anomalies at 450 m (Figure 9). The region has been divided into four subregions, according to the differences in the distribution of the data and anomalies (Table 2). The percentage of anomalies of the data is highest in the northwest region, indicating the higher probabiliy ($8.7 \pm 0.5\%$) of finding rings there; the second

number is the 90% confidence limits.[1] Very few rings are expected to
be found in the southwest region, indicated by the low percentage of
anomalies (1.1 ± 0.2%). Although the percentage anomalies in the two
eastern regions is about 5%, the much larger 90% confidence intervals
(about 1 and 2%), due to much smaller data density, make it difficult
to conclude that rings exist. Temperature anomalies at 400 and 700 m
were also used but they did not contribute any additional ring obser-
vations. Temperature at 300 m were only used supplementally because
of the small temperature gradient between 300 and 450 m in the Eighteen
Degree Water at these depths.

It appeared that some of the data from the same set of instruments
or vessels were of questionable quality. Individual temperature pro-
files were checked for possible errors (incorrect positions, inver-
sions, spikes, etc.) and those that looked suspicious were discarded.
Ring observations were checked by comparing them to non-anomalous ob-
servations; if there was a conflict, the ring observation was dis-
carded. In the ring observations and time-series, 697 (69%) of the
total anomalies, were used.

Temperature and salinity measurements taken inside cold rings re-
vealed a difference in the T-S relation from that of the Sargasso Sea

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[1]If P is the proportion of success (i.e. the probability of success)
in a sample of size N drawn from a binomial population in which p is
the proportion of success, then the confidence limits for p are given
by $P \pm Z_c \sqrt{\dfrac{p(1-p)}{N}}$ where Z_c is the confidence coefficient. All the

confidence intervals computed in this study were done by assuming all
the temperature records are independent and using the sample proportion
P as p.

(Molinari, 1970; Cheney and Richardson, 1976), indicative of the presence of Slope Water (Iselin, 1936) in the core of the rings. Some of the rings observed in this study have this additional supporting measurement which documented that they were indeed rings (see Appendix B). Not all ring observations in this study were so documented but the six that were give us confidence that others really are rings.

IV. RESULTS

Cyclonic Gulf Stream Rings

Forty-two ring observations were identified when the ring criteria
were applied. An additional twenty-eight rings were obtained from
other sources mentioned previously (Figure 10). The movement of indivi-
dual rings was inferred from these seventy ring observations, together
with single anomalies which did not satisfy the ring criteria. Twelve
ring time-series and fifteen single ring observations were obtained
(Figure 11, 12). Some of these single rings may be repeated observa-
tions of the same rings separated widely in time and space. Five of
the time-series were long, covering a period from one to two years.
An additional six series were established using only one or two anomalies.

The majority of the rings were found in the western, or the north-
western Sargasso Sea, where the highest data density was located. Nine
rings (four in 1970, three in 1971, one each in 1972 and 1973) appeared
to be formed between 60° and 70°W. Other rings might have formed in
this region but were not observed. Four rings moved westward until
they were within 200 miles of the Gulf Stream. Then they turned south-
west and moved along a path parallel to the Gulf Stream and appeared to
coalesce with the Stream near Florida. Six rings moved down this path
during the four years under study, an average rate of one and a half
per year. Since there may have been rings not observed, this should
represent a minimum rate. If the rings were assumed to be formed be-
tween 60° and 70°W and moved with an average speed of 3 km a day, the

average life span of rings following this path would be about two to three years.

Three rings were found south of 30°N in the western region and far away from the Gulf Stream. These rings also appeared to move south-west. Their motion may consist of a larger southward component into the Sargasso Sea compared to the westward motion discussed above. The fate of these rings remains unknown from these limited observations.

Three rings were found in the region east of 60°W which Parker (1971), using shallower mechanical BT's, had found to be devoid of rings. There is limited evidence that these rings also moved west-ward.[2] However, the low data density in this region prevents any de-tailed description of distribution and movement of rings there. No rings were found in an area south of 30°N and east of 65°W. Although there were some temperature anomalies in this region, the data were too sparse to meet the ring criteria. Thus, the question of whether rings are found in this region remains unresolved.

Rings moved with various speeds, ranging from 1 to 7 km a day (Figure 13). Speeds were estimated from the positions of the center of adjacent ring observations, sometimes rather subjectively, especially when there were few anomalies in a ring observation. Speed varied not only from ring to ring, but also along the path of the same ring. However, 82% of the speeds lie within 1 to 4 km a day, and the mean is 2.7 km a day which can be considered as typical mean ring translation rate.

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[2] Recent measurements in 1975 and 1976 (McCartney, 1975a) have con-firmed these observations and indicated that large rings can be found in this region (see Appendix H).

Although most ring tracks appeared to be smooth, some rings made abrupt changes in speed and direction. The large time separation between consecutive ring observations and the difficulty in estimating the ring centers prevented details of the motion as was reported by Fuglister (1972).

In order to estimate the number of rings coexisting at a single time, the data was scrutinised for the time of highest data density and greatest number of rings and time-series. November 1971 was chosen because it was near the middle of the four-year period under study and, more important, it was the time of MODE-0 when numerous measurements were being made in the western Sargasso Sea. Ring positions during November 1971 were estimated, using the rings' apparent direction of motion and an average speed of 2.7 km a day. Eleven rings were found to exist at that time, mostly in the western Sargasso Sea (Figure 14, Table 4). The positions of a few single rings have not been extrapolated because of their unknown directions of motion. The low data density in the eastern and southeastern part of the region suggests the possibility that additional rings could have existed there and that the above number may be a low estimate.

Warm Eddies

Of the total data at 600 m, 2% were found to be warm temperature anomalies corresponding to a downward displacement of isotherms of at least 150 m (Table 5). Two warm "ring observations" satisfying the ring criteria were obtained; these will be termed warm eddies since warm rings are only found to the north of the Gulf Stream. There were

five other observations each with two anomalies (Figure 15). Of these
seven observations, two were close to the Gulf Stream and three near
the MODE region.

The XBT traces of these warm observations showed a thick (several
hundred meters) layer of water with a small temperature gradient (17°
to 19°C) between 300 and 600 m; sometimes part of the layer was iso-
thermal. The layer was accompanied by a deepening of the main thermo-
cline. The two warm eddies near the Gulf Stream showed maximum vertical
displacements of more than 200 m (Figure 16) while the displacement of
others were near 150 m.

Efforts were made to analyse the 450-meter XBT's but special care
was needed since a 150 m increase in depth of the isotherms at this
level corresponds to a temperature change of less than 1.0°C. Only
in two cases were there sufficient data to provide convincing evidence
of the warm eddies. On one occasion more than 300 XBT's taken within
a month in a region bounded by 33-38°N and 63-69°W made a detailed
study of one of the eddies possible. Water of 18°C was found down to
a depth of 450 m or more among three cold rings. It is impossible from
the data to tell whether there was a corresponding dip in the main
thermocline under this layer but unless the vertical temperature
gradient was much larger than usual, the thermocline had to be deeper.
When the data from October 20 to 24 and November 1 to 4 were combined,
there was a suggestion that the warm eddy moved rapidly westward with
a rate of 20 km a day.

These warm eddies are characterized by the extra thick layer of
Eighteen Degree Water extending from 200 to 600 m, as compared with the

usual depths of 200 to 400 m. Beneath the layer, there is a correspond-
ing deepening of the main thermocline of more than 150 m. The extent
of the 18° isotherm at 450 m, or 17° at 600 m, both of which correspond
to about a 150 m height anomaly, suggests that these features have a
horizontal scale of less than 100 km. However, no detailed survey of
these warm eddies was made and the shape of them remains largely un-
known. If geostrophy and a deep layer of zero velocity are assumed,
a clockwise circulation in these eddies is obtained.

V. DISCUSSION

Cyclonic Gulf Stream Rings

From this study, it appears that there are two types of ring move-
ment, both of which showed a net southwest displacement over long
periods of time. Some rings moved westward until they came close to
the Gulf Stream. On approaching the Stream, they turned abruptly and
moved southwestward and appeared to coalesce with the Stream near Florida.[3]
Other rings took a more southward direction into the Sargasso Sea after
their formation. The results of this study, together with other obser-
vations (Fuglister, 1972; Parker, 1971; Stumpf, Strong and Pritchard,
1973; Richardson, Strong and Knauss, 1973) suggest that the first type
of movement may be a common phenomenon. From the limited observations,
it is not clear how typical is the second type of movement and what
ultimately happened to the rings on this path. It is likely that they
decayed to a point beyond recognition as Gulf Stream rings and may have
appeared as "cold spots" in the southern Sargasso Sea (Draft Synoptic
Atlas; Wunsch, 1975).

The processes that cause the movement of rings have not been de-
termined. Rings may simply be advected by the general mean flow in
the Sargasso Sea. On the other hand, the movement may be self-induced.

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[3]There have been no direct observations of a ring coalescing with the
Gulf Stream in this region. Rings appear to consistently move towards
Florida where they have been observed to be partially attached to the
Stream (Cheney and Richardson, 1975; Richardson, 1976). The simplest
explanation of the available data is that these rings eventually co-
alesce with the Gulf Stream.

Circulation in the North Atlantic is dominated by the subtropical gyre consisting of a narrow and fast Gulf Stream in the west and north and broad, slow southwestward flow in the Sargasso Sea (Iselin, 1936; Sverdrup, Johnson and Fleming, 1942; Worthington, 1977). Recent SOFAR float tracks in the northwestern Sargasso Sea provided further evidence of this southwestward flow (Cheney, et al., 1976). Part of the down-stream increase in the transport of the Gulf Stream (Knauss, 1969) is thought to be recirculated by means of this return flow. Speeds of a few km per day are required in the inflow to the Stream to account for the transport increase. Thus the southwest movement of the rings in the Sargasso Sea is consistent with the speed and direction of the mean circulation of the region.

However, the abrupt change to a more southward direction of motion of the rings close to the Gulf Stream is puzzling. Countercurrents are known to exist on both sides of the Stream (Wust, 1936; Munk, 1950; Stommel, 1965). But the countercurrent is too narrow (about 50 km wide), swift (more than 20 cm/sec), shallow (about 200 m deep) and inter-mittent to account for the movement of rings there. Some unknown pro-cesses, probably from the interaction between the Stream and rings, may cause this type of movement.

Rings may be self-propelled through the surrounding fluid. Several theoretical studies have been made of the self-induced motion of the rings. Warren (1967) suggested the westward movement might be caused by the beta-effect and, similarly, by sloping bottom topography. The westward movement may also be explained by representing rings either as a packet of linear baroclinic Rossby waves (Flierl, in preparation) or

as linear barotropic Rossby waves in a lateral shear (Yamagata, 1975). Flierl (in preparation) suggested the southward movement might be caused by the asymmetry of the rings. Stern (personal communication) suggested that the southward movement of rings may be related to the decay of the ring coupled with the conservation of potential vorticity. This theory agrees reasonably well with observations (Cheney and Richardson, 1976).

Since Gulf Stream rings probably do not extend to the bottom as coherent structures (Fuglister, 1972), except possibly during a short period immediately after their formation, bottom topography is probably not an important factor in determining their movement. However, the sudden change in direction of Ring 3 near Bermuda and the tendency of rings to coalesce with the Gulf Stream north of the Bahama Islands strongly suggest the presence of land masses does affect ring movement.

Rings east of 60°W

Three cold rings were found in a region east of 60°W which was found to be devoid of cold anomalies by Parker (1971). There is evidence that they also moved westward. McCartney (1975a) reported the recent discovery of several large cold features in this region. They have a 300 m uplifting of the main thermocline and a diameter of over 200 km. Worthington (1976) suggested calling them Gulf Stream Extension Rings. Some of these rings showed anomalously high oxygen content in the 12° to 17°C temperature range (Worthington, 1976). suggesting they were also rings with Slope Water cores. Recent studies associated with POLYMODE have added significantly to the data base, the number of

anomalies and rings found in this area. These recent observations are analysed in Appendix H.

One Gulf Stream Extension Ring showed strong Mediterranean Water influence (McCartney, 1975a) possibly indicating an origin further east. A recent XBT transect (Seaver, 1975) across the Atlantic along 34° 30'N shows what may turn out to be large cold rings as far east as the Mid-Atlantic Ridge (35-40°W). However, the question of where and how they formed remains unexplained. The center core may contain Slope Water (Iselin, 1936) or Northern Gyre Water (Worthington, 1976). It appears that Gulf Stream Extension Rings move into the region west of 60°W. If so, it is very likely that some of the "ring observations" were actually these big rings.

Number and Spacing of Rings

Fuglister (1972) estimated that five to eight cyclonic rings are formed each year. If this number and an average life span of a ring of two to three years are assumed, ten to fifteen rings are expected to exist at a time. This estimate agrees closely with the eleven ring observations during November 1971 and the recent near-synoptic ring survey of the area (Cheney and Richardson, 1975). The low data density in the eastern regions suggests the possibility that additional rings could have existed there and that the above number may be a low estimate.

It appears that generally the spacing between centers of adjacent rings is about 300 to 400 km; sometimes the spacing between rings can be very small. The centers of Ring 2 and Ring 3 in November 1971 were

less than 200 km apart. These two rings were exceptionally well documented so that it is clear they were spearate before December 1971. It is not known what happened to them after December. Did they merge into one or repel each other? There is indication that splitting of rings has occurred (Cheney, et al., 1976). Fuglister (1972) suggested his two rings came together and moved apart. The merging and splitting of rings (or Gulf Stream Extension Rings) should have profound influences on the dynamics of the rings and the neighboring fluid but it remains to be documented.

Warm Eddies

The results of this study, together with closely spaced XBT transects (Gulf Stream Monthly Summary; Noble, 1975) indicate that warm eddies with vertical displacements of more than 150 m exist in the Sargasso Sea although they occur less frequently than the Gulf Stream rings. Warm anticyclonic rings have been observed to break off on the shoreward side of the Gulf Stream (Saunders, 1971) but the Stream prevents them from moving into the Sargasso Sea. Thus the warm eddies found in this study have to be formed by mechanisms other than ring formation via Gulf Stream meanders.

Warm eddies appear to be similar to the anticyclonic "rotating lens" of Eighteen Degree Water observed by Swallow (1971). A deepening of more than 150 m of the main thermocline was found beneath the thick layer of Eighteen Degree Water. Velocities of about 50 cm/sec were observed in the Aries eddy (Swallow, 1971) which extended to a depth of 2000 m. There was no velocity measurement in the warm eddies found in

this study but if geostrophy and a deep layer of no motion are assumed, an anticyclonic circulation is obtained. Other mid-ocean eddies observed by Swallow (1971), Koshlyakov and Grachev (1973), Gould, Schmitz and Wunsch (1974) and in MODE were of smaller displacement (about 50 m) and the thick layer of Eighteen Degree Water was absent.

Worthington (1959, 1971, 1972) suggested that the deepening of the main thermocline can be caused by the sinking of surface water as it is cooled by the Continental Polar Air in the winter. But his analysis only showed the Eighteen Degree Water influence in the upper 400 m. Sections across the warm eddies showed wavelike structures over a small region (about 100 km) instead of a general deepening of the main thermocline over a large area. In addition, no seasonal periodicity was found in the variation of thermocline depth. Therefore, Worthington's suggestion does not appear to explain the eddies.

Sources of mesoscale energy, and in particular, mid-ocean eddies, are being investigated by POLYMODE scientists and others. One of the possible sources are rings. Several theoretical studies have focussed on the interaction between ring-like features and the surrounding fluid and these studies have suggested features that could be interpreted as warm eddies. It was shown that westward moving obstacles generate meandering wakes in a stratified rotating fluid (McCartney, 1975b) and when the wakes become large enough, warm eddies are generated (McCartney, 1976). Flierl (in preparation) suggested that dispersed waves are left behind by moving and decaying rings, resulting in a series of highs and lows with decreasing amplitude east of the ring. The low

could be interpreted as a warm eddy near the ring. Stern (1975) suggested the existence of a closely packed array of coupled cyclonic-anticyclonic systems called "modons", each with a minimal vorticity. This array can be viewed as cold rings intermixing with warm eddies.

Some of the warm eddies observed in this study might be associated with cold Gulf Stream rings. One eddy was found among three rings and Noble's (1975) warm eddy was between two rings. Thompson and Gotthardt (1971) reported a similar but opposite phenomenon: a cold "upwelling" region behind a warm ring north of the Gulf Stream in the Slope Water region. Thus there is a possibility that warm eddies could be generated by rings as some theories predict. It has been suggested that the evolution of these waves is slow, on the order of months, for baroclinic rings (Flierl, in preparation). This is consistent with the observation that warm eddies are not frequently found as rings. Transects across Gulf Stream rings may show these waves at earlier stages of development and hence the waves were not noticed. More detailed observations in the vicinity of rings are needed to explore the possible generation of eddies by rings.

VI. SUMMARY AND CONCLUSIONS

Approximately 50,000 temperature records, mainly XBT's, were obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central and analysed to study the general distribution and movement of cyclonic Gulf Stream rings. The data were taken from 1970 through 1973 in the region bounded by 20-40°N and 50-80°W. Additional ring observations from other sources, including the Gulf Stream Summary (1970-73) and satellite photographs, were also used.

A "ring observation" was defined to consist of three or more height anomalies of 150 m within a five day period and within a diameter of 100 km. The height anomaly means a vertical displacement of the thermocline from its mean depth. Seventy ring observations were identified; they constitute twelve ring time-series, together with fifteen single rings. By extrapolating their movement in time and space, eleven rings were found to exist at one time (November 1971).

Rings were concentrated in the northwestern Sargasso Sea where the data was densest. Nine formed from the Gulf Stream between 60° and 70°W. They typically moved westward, turned southwestward when they were within 200 miles of the Gulf Stream and appeared to eventually coalesce with the Stream near Florida. A minimum of about one and a half rings moved down this path a year, with a mean speed of about 3 km per day and an estimated life span of two to three years. Some rings appeared to move in a more southward direction into the Sargasso Sea after their formation.

Some rings were found in a region east of 60°W which had previously been found devoid of rings (Parker, 1971). However, the low data density there prevented detailed study of the region, especially in an area south of 30°N and east of 65°W where the data were too scarce to meet the ring criteria.

Several warm eddies, with negative height anomalies of at least 150 m, were found in the data. They typically consisted of a thick layer of Eighteen Degree Water extending down to 600 m with a corresponding dip in the main thermocline. Anticyclonic circulation in these eddies was obtained if geostrophy and a deep layer of no motion are assumed. The eddies were found much less frequently than cold rings and because of the limited data, their distribution and movement cannot be inferred.

TABLE 1. Summary of the data.

Types of Records	Fleet Numerical Weather Central	National Oceanographic Data Center	Total Number
XBT's	29,194	18,421	47,615
STD stations	117	1,073*	1,190
Hydrostations	161	0*	161
	29,472	19,494	48,966

* The NODC data file does not distinguish between STD's and hydrostations.

TABLE 2. Summary of 150 m Height Anomalies at a depth
of 450 m. The number in parenthesis is the
90% confidence limits (see text).

		1970	1971	1972	1973	Total
North-western Sargasso Sea	# of Data	3,194	3,268	1,627	1,822	9,911
	# of Anomalies	335	234	113	184	866
	Percentage	10.5	7.2	6.9	10.1	8.7($\pm$0.5)
South-western Sargasso Sea	# of Data	722	2,605	1,171	797	5,295
	# of Anomalies	13	24	10	12	59
	Percentage	1.8	0.9	0.9	1.5	1.1($\pm$0.2)
North-eastern Sargasso Sea	# of Data	261	411	330	222	1,224
	# of Anomalies	12	19	16	18	65
	Percentage	4.6	4.6	4.8	8.1	5.3($\pm$1.1)
South-eastern Sargasso Sea	# of Data	40	126	92	115	373
	# of Anomalies	5	5	4	4	18
	Percentage	12.5	4.0	4.3	3.5	4.8($\pm$1.8)

TABLE 3. Summary of 100 m Height Anomalies at a depth of 450 m. The number in parenthesis is the 90% confidence limits (see text).

		1970	1971	1972	1973	Total
North-western Sargasso Sea	# of Data	3,194	3,268	1,627	1,822	9,911
	# of Anomalies	437	320	164	235	1,156
	Percentage	13.7	9.8	10.1	12.9	11.7($\pm$0.5)
South-western Sargasso Sea	# of Data	722	2,605	1,171	797	5,295
	# of Anomalies	31	96	23	19	169
	Percentage	4.3	3.7	2.0	2.4	3.2($\pm$0.4)
North-eastern Sargasso Sea	# of Data	261	411	330	222	1,224
	# of Anomalies	22	29	28	18	97
	Percentage	8.4	7.0	8.5	8.1	7.9($\pm$1.3)
South-eastern Sargasso Sea	# of Data	40	126	92	115	373
	# of Anomalies	5	5	5	6	21
	Percentage	12.5	4.0	5.4	5.2	5.6($\pm$2.0)

TABLE 4. Observations of the 11 rings
during November 1971.

Rings[*]	Last Day of Observation	Platform/ Agency	Observations	Remarks[**]
A(1)	November 5,9, 1971	Sumner, FNWC	3 XBT's	
B(2)	November 7, 1971	Lynch	15 XBT's	
C(3)	October 20–23, 1971	Steinaker	4 XBT's	
D(10)	October 19, 1971	FNWC	1 XBT	
E(5)	June 20,21,28 1971	J. Daniels	3 XBT's	southwest movement for 5 months
F(6)	August 6, 1970	FNWC	1 XBT	southwest movement offshore of the Stream for 15 months
G(S)	November 14, 1971	Lynch	5 XBT's	
H(S)	March 2,3, 1972	Chain	5 XBT's	westward movement for 4 months
I(S)	September 30, October 2, 1971	FNWC	6 XBT's	
J(S)	September 17, 18, 1971	Franconia	11 XBT's	southwest movement for 2 months
K(S)	August 14–17, 1971	Sims	8 XBT's	southwest movement for 3 months

* The letters identify the rings shown in Figure 15. Inside the parenthesis in the number of the time-series in which the ring observation belonged, or S if the observation was associated with a single ring.

** This indicates the assumed movement of the ring used in interpolating the result.

TABLE 5. Warm Anomalies at 600 m.

Year	Number of Data	Number Anomalies	Percentage
1970	1,020	24	2.3
1971	794	10	1.3
1972	698	16	2.3
1973	875	13	1.5
	3,387	63	1.9

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Figure 1. Schematic diagram of the formation of a cyclonic ring
in June 1970 (based on data from the Gulf Stream
Monthly Summary, 5(6), 1970). From Richardson, 1972.

Block 1: 10-11 May   Meander begins to form

Block 2: 20-21 May   Loop forms to south

Block 3: 1 June   Cold water mass is isolated

Block 4: 8 June   Ring is detached.

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Block 4: 8 June Ring is detached.
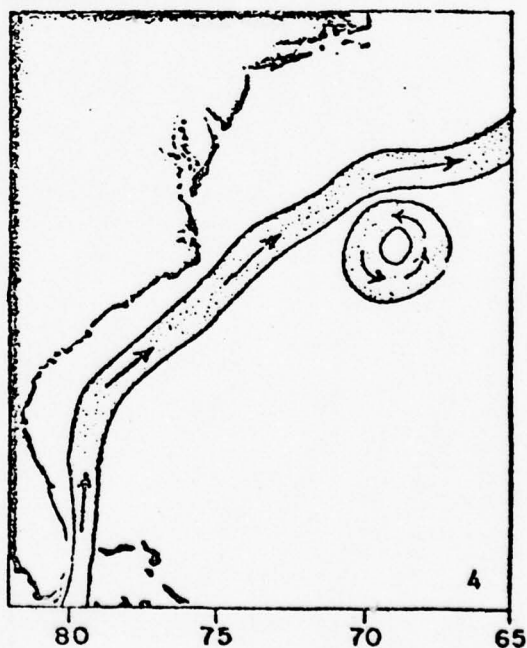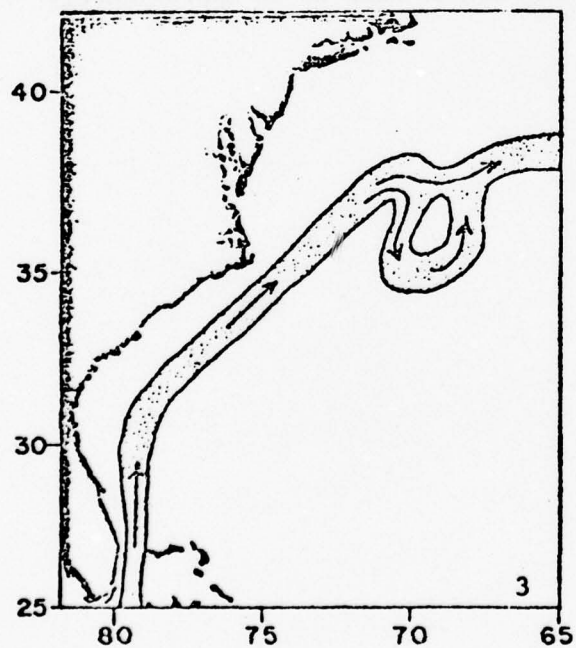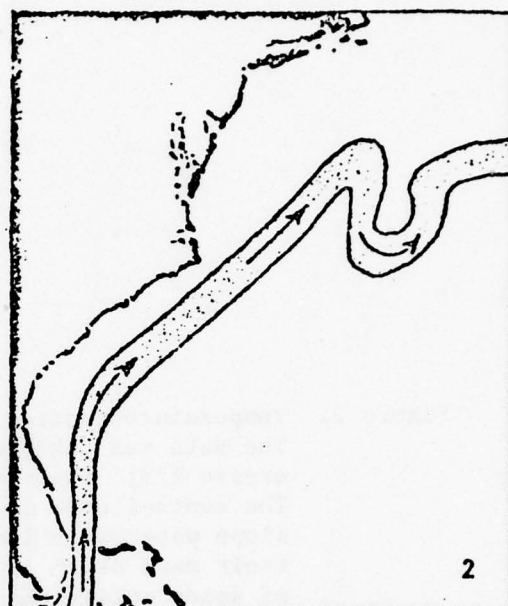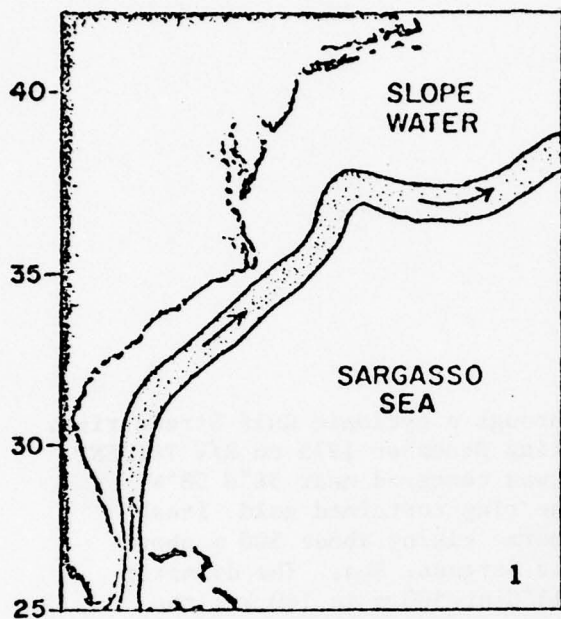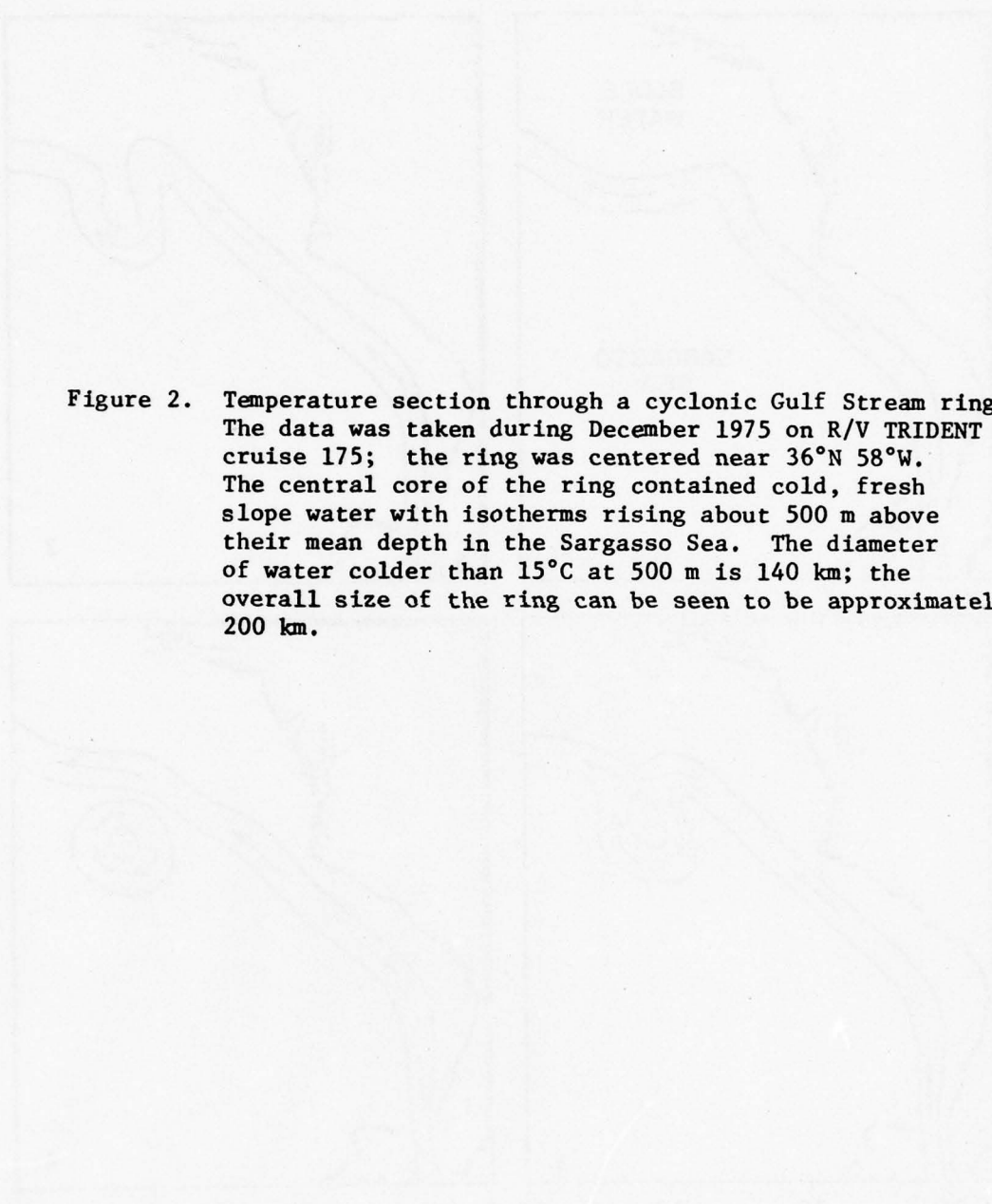
Figure 2.   Temperature section through a cyclonic Gulf Stream ring.
The data was taken during December 1975 on R/V TRIDENT
cruise 175; the ring was centered near 36°N 58°W.
The central core of the ring contained cold, fresh
slope water with isotherms rising about 500 m above
their mean depth in the Sargasso Sea. The diameter
of water colder than 15°C at 500 m is 140 km; the
overall size of the ring can be seen to be approximately
200 km.

XBT LOCATIONS

DISTANCE (KILOMETERS)

DEPTH (METERS)
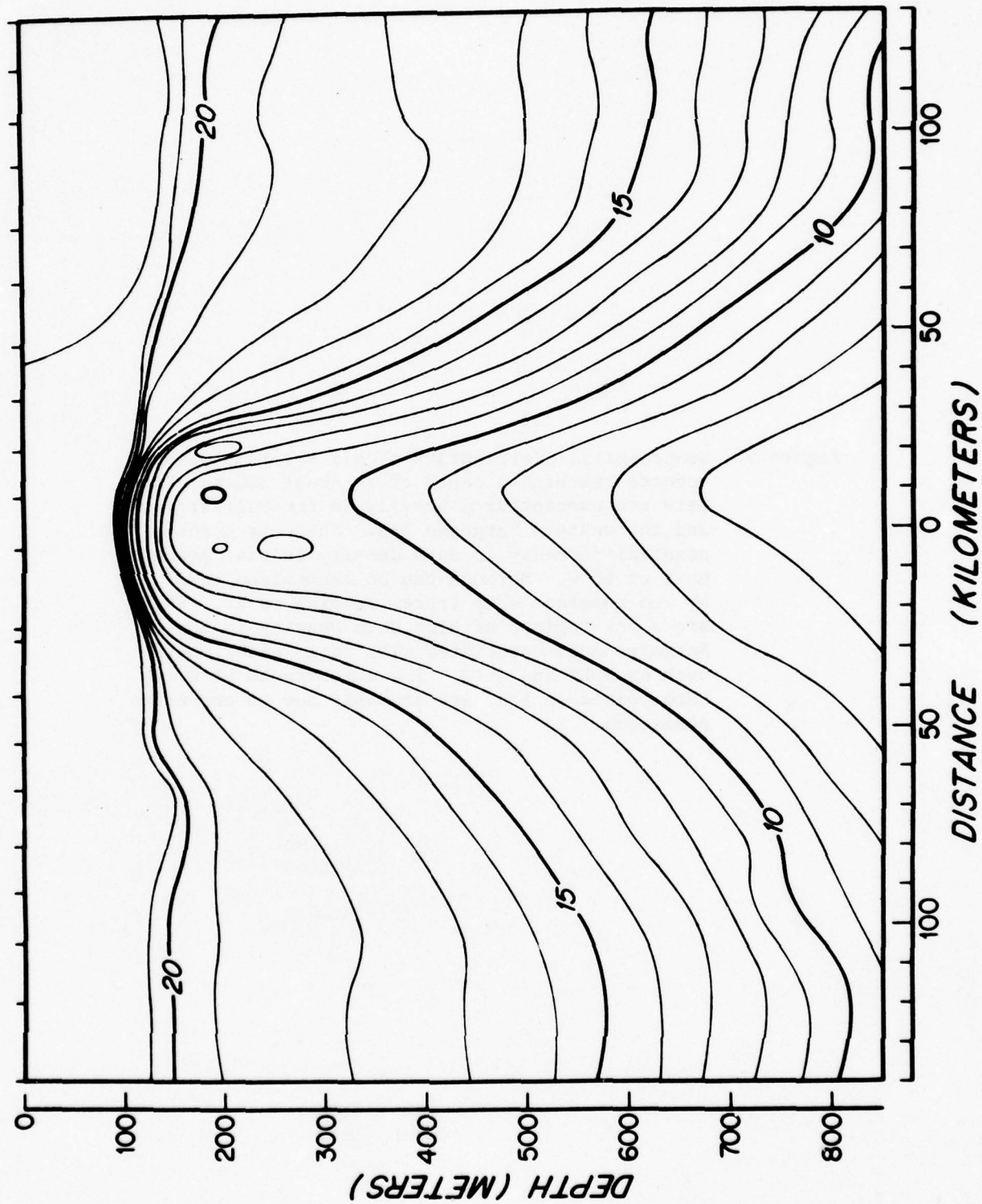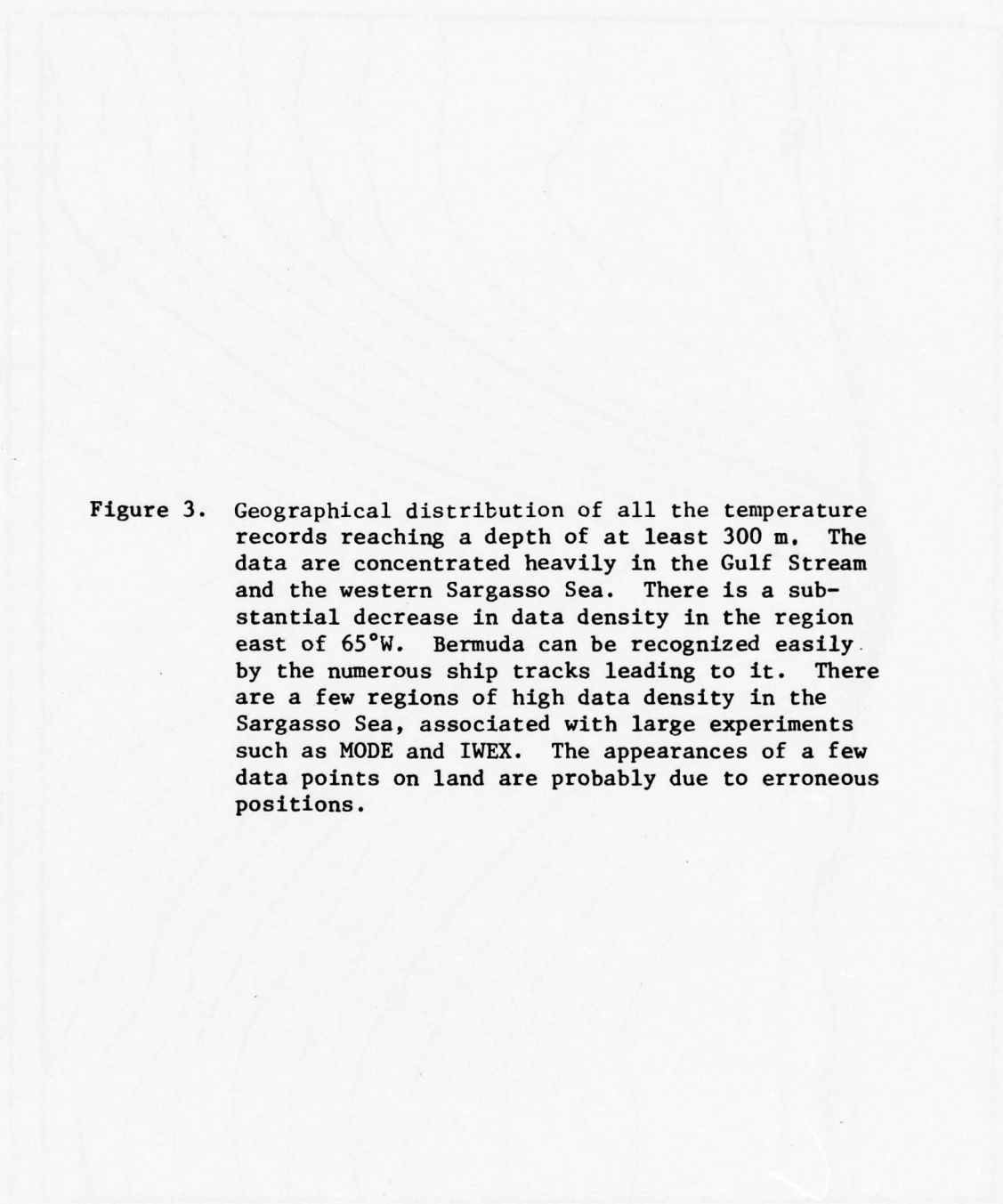
Figure 3. Geographical distribution of all the temperature records reaching a depth of at least 300 m. The data are concentrated heavily in the Gulf Stream and the western Sargasso Sea. There is a substantial decrease in data density in the region east of 65°W. Bermuda can be recognized easily by the numerous ship tracks leading to it. There are a few regions of high data density in the Sargasso Sea, associated with large experiments such as MODE and IWEX. The appearances of a few data points on land are probably due to erroneous positions.
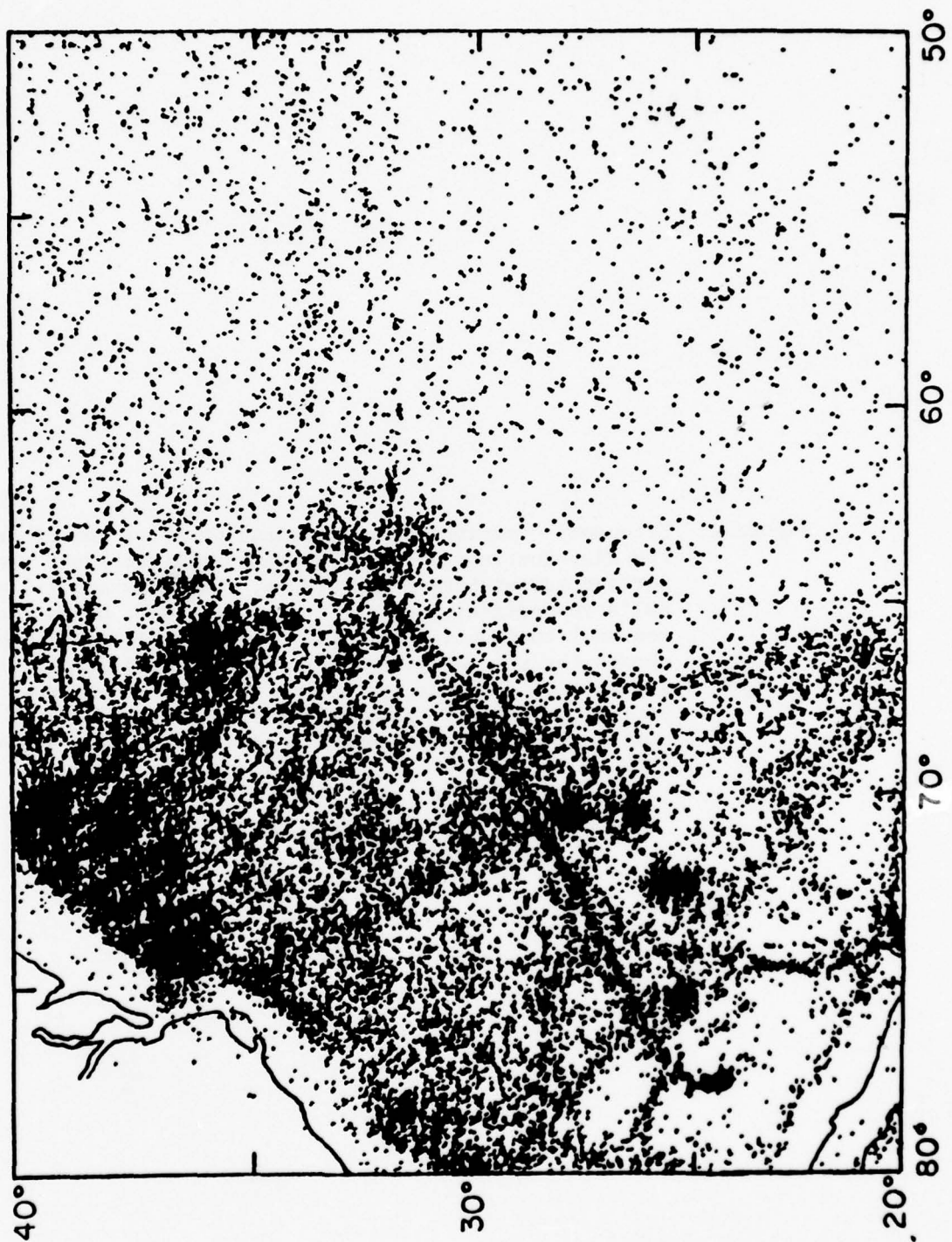
Figure 4. Frequency distribution of terminal depth of the records.
The distribution is trimodal; the peaks represent the
surface temperature measurements, the 450 m and 750 m
XBT's respectively. Since most of the data below the
seasonal thermocline were 450 m XBT's, this level was
chosen for the main analysis. Large fluctuations in
sea surface temperatures due to seasonal and shorter
period variability, prevented the effective use of
surface temperature records in identifying ring anomalies.

Figure 2. Frequency distribution of temperature records in the MSTS in the grid zone defined (see section 4). Peaks occur near 0, 400, and 750 meters. Many appear clustered between 0 to 400 m, with the second peak near 400 meters, corresponding to terminating records. They are related to the instrumentation associated with each type of terminal depth.
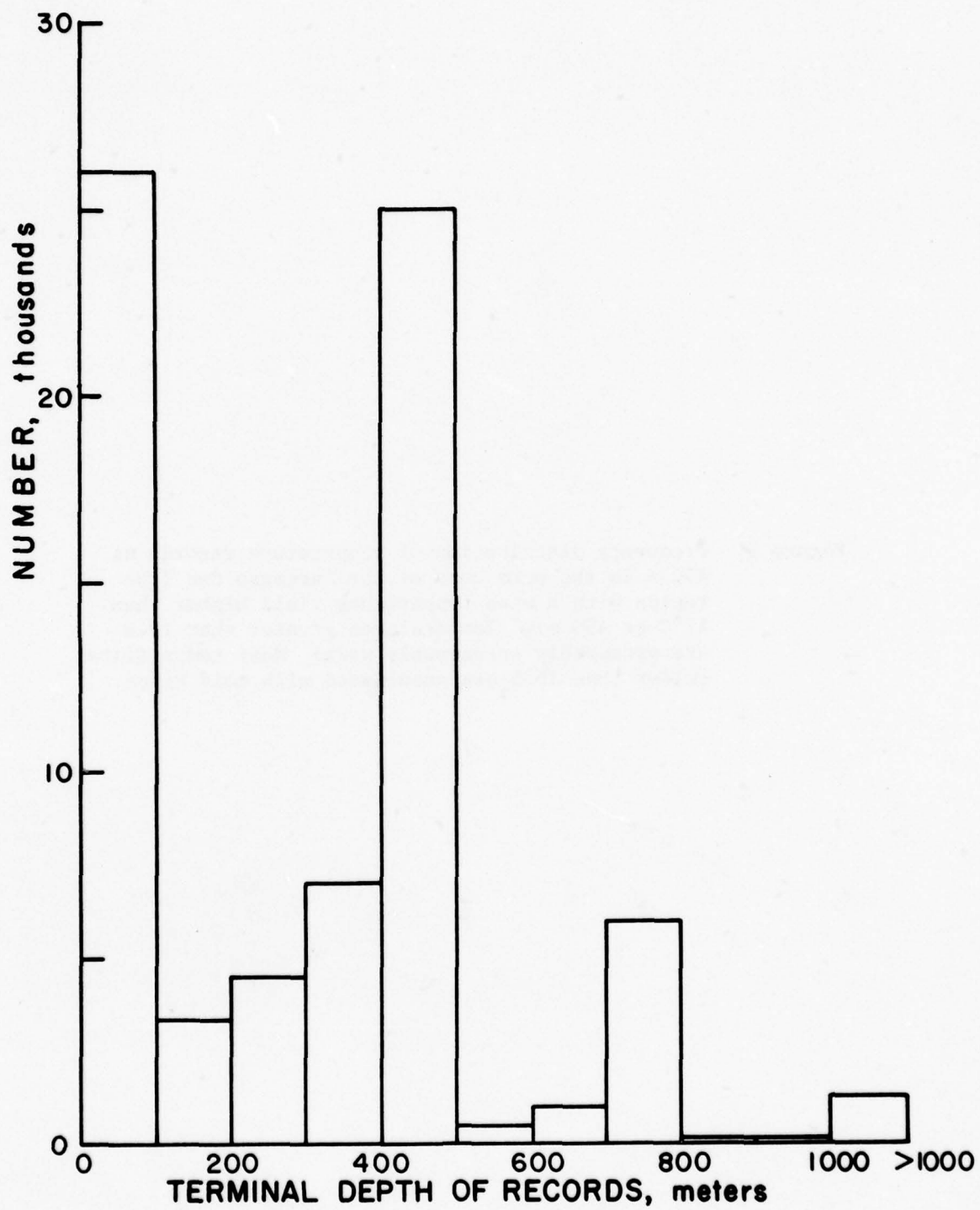
Figure 5.   Frequency distribution of temperature records at
            450 m in the warm core of the Sargasso Sea (the
            region with a mean temperature field higher than
            17°C at 450 m).   Temperatures greater than 19.0
            are presumably erroneously warm.   Most temperatures
            colder than 15.5 are associated with cold rings.
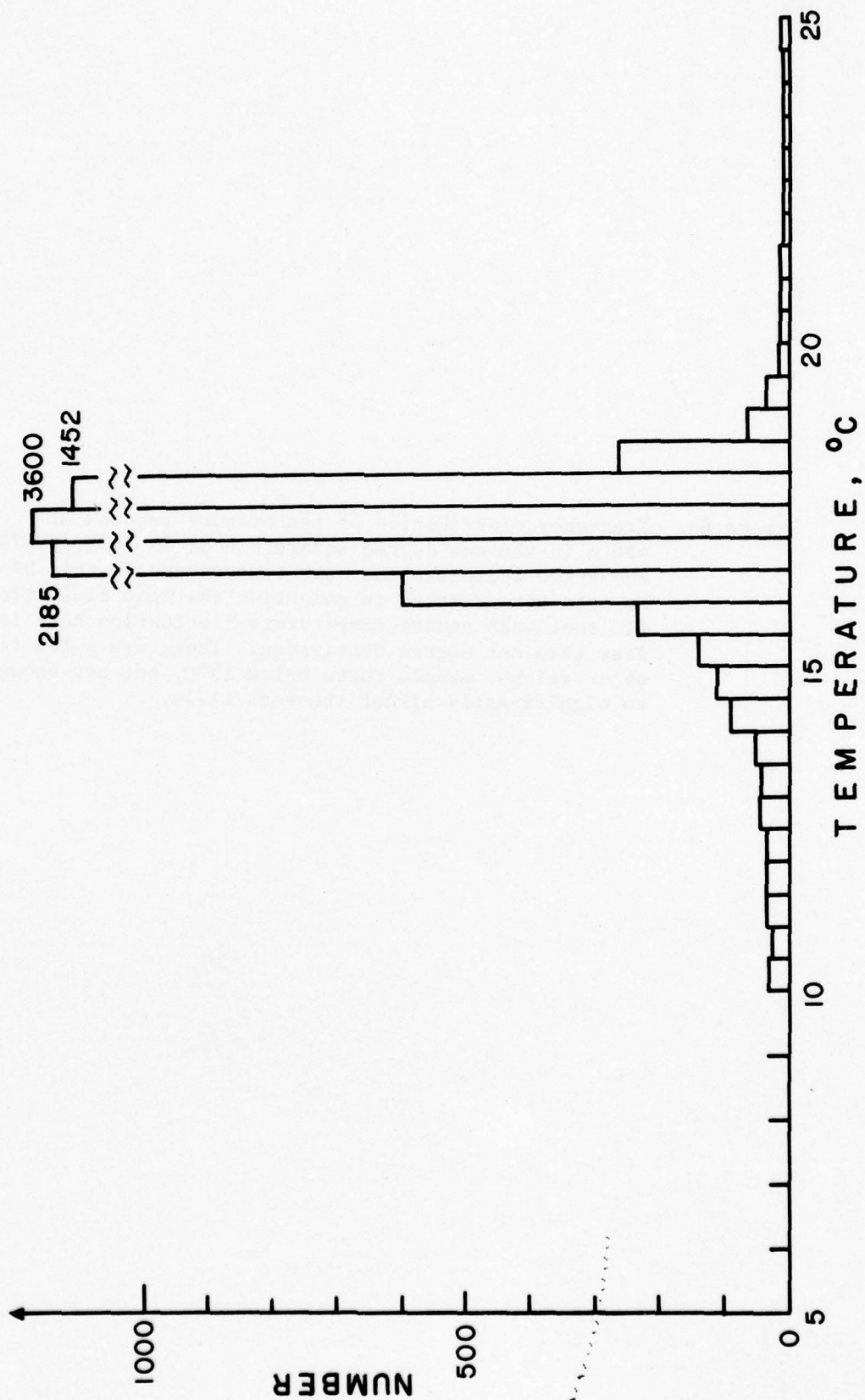
Figure 6a. Frequency distribution of temperature records at
450 m in the one degree square bin of 33-34°N, 69-70°W.
The arrow indicates the mean temperature in this bin.
No data were removed in computing the mean field since
the root mean square temperature fluctuation here is
less than one degree Centigrade. There are a few ring
observations, namely those below 15°C, but not enough
to significantly affect the mean field.
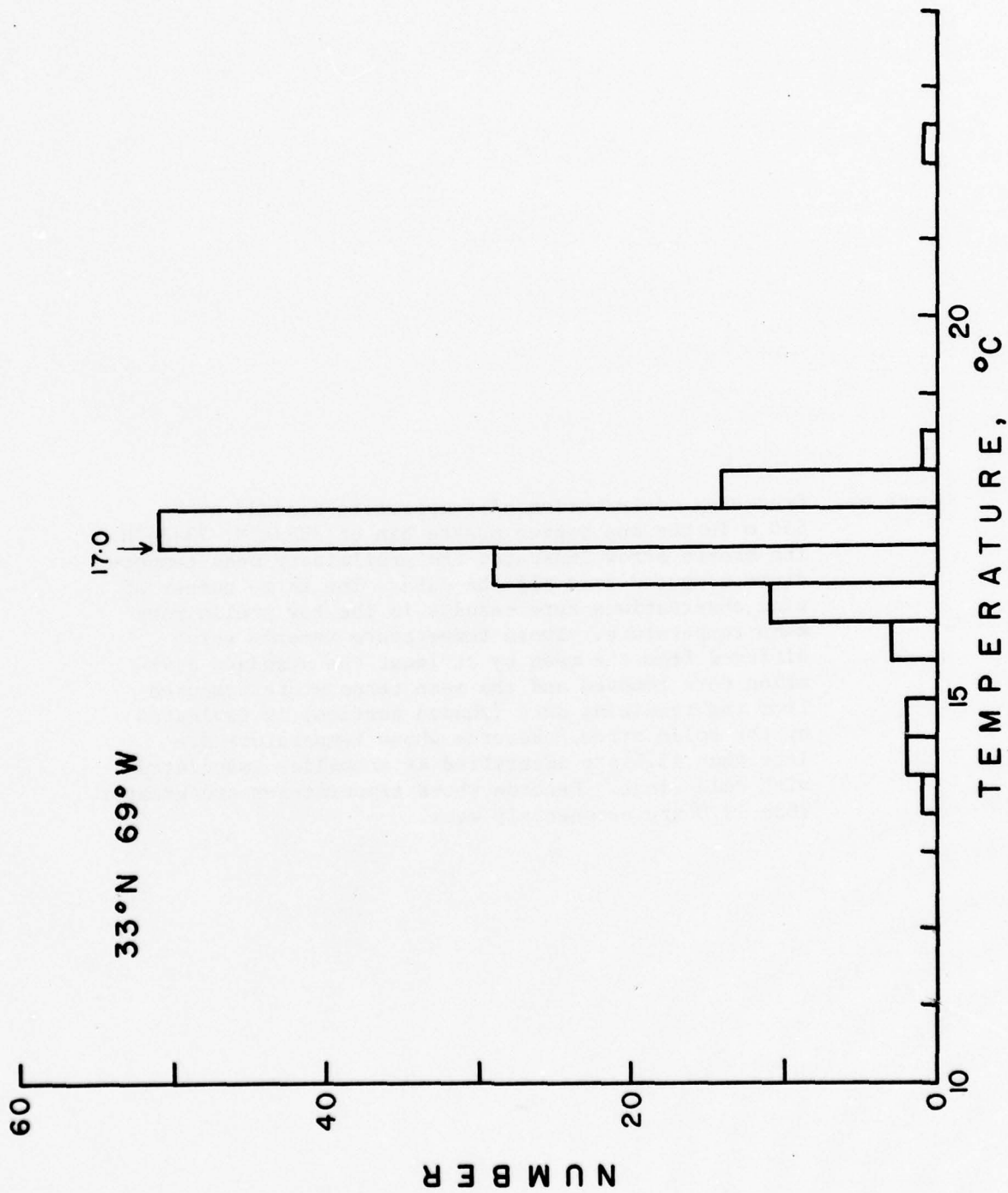
Figure 6b. Frequency distribution of temperature records at
450 m in the one degree square bin of 33-34°N, 73-74°W.
The broken arrow indicates the preliminary mean temper-
ature computed from all the data. The large number of
ring observations here results in the low preliminary
mean temperature. Those temperature records which
differed from the mean by at least one standard devi-
ation were removed and the mean temperature computed
from the remaining data (shaded portion) is indicated
by the solid arrow. Records whose temperature are
less than 15.5° are identified as anomalies associated
with cold rings. Records whose temperatures are greater
than 19.0° are erroneously warm.

33°N 73°W

TEMPERATURE, °C

NUMBER
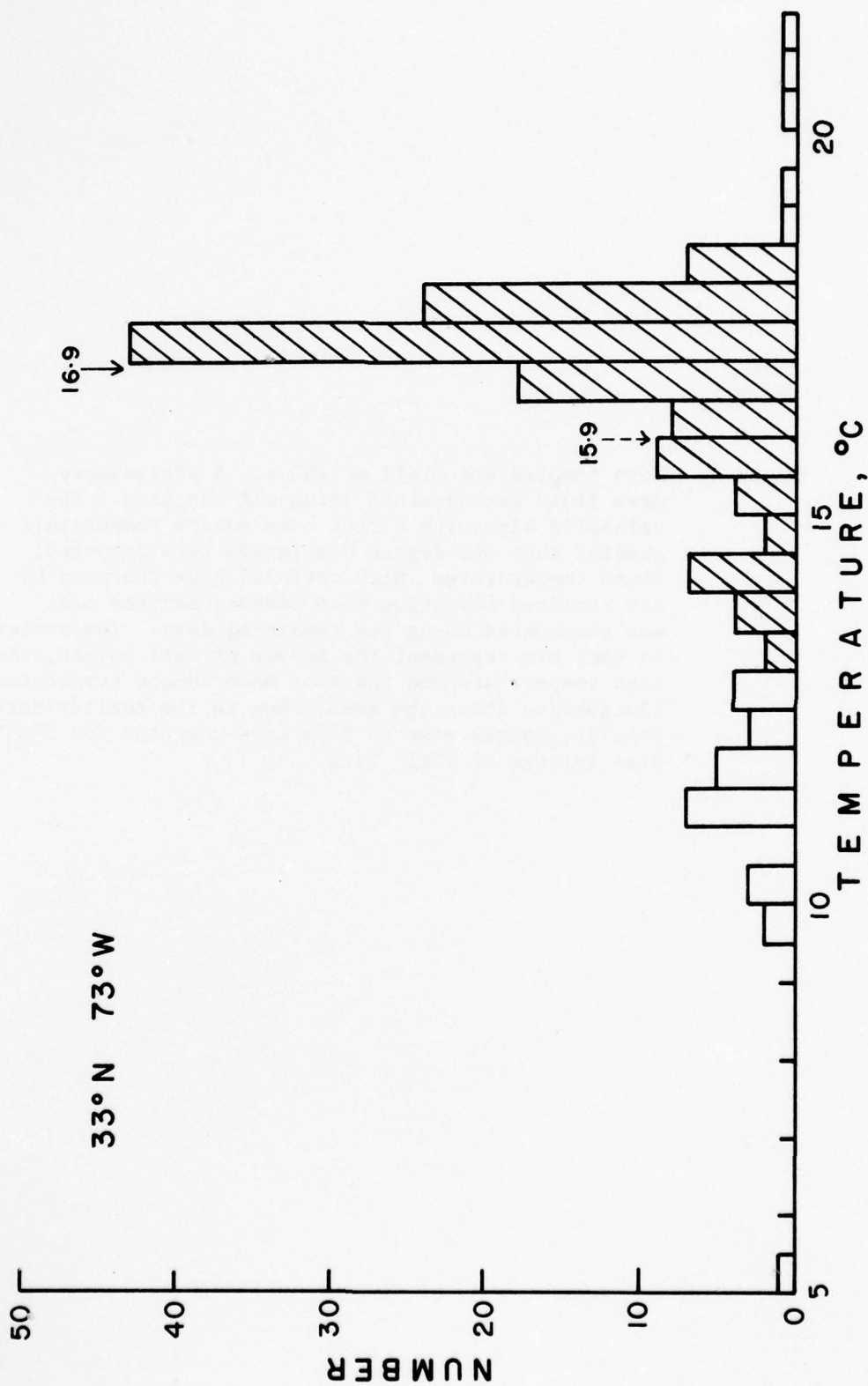
Figure 7. Mean temperature field at 450 m. A preliminary
mean field was obtained using all the data. The
values in bins with a root mean square temperature
greater than one degree Centigrade were computed;
those temperatures which deviated from the mean by
one standard deviation were removed and the mean
was recomputed using the remaining data. The numbers
in each bin represent the number of data points, the
mean temperature and the root mean square temperature
fluctuation about the mean. Due to the smaller data
density, values east of 68°W were computed for 2°X3°
bins instead of 1°X1° bins.

DATA AT 450 METERS

LONGITUDE

LATITUDE

50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81

20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

Figure 8a-c. Contours of mean temperature at depths of 300, 450 and 700 m respectively. Contours were obtained by linear interpolation of temperature values of adjacent bins. The Gulf Stream is shown clearly as the regions of high horizontal temperature gradient. At 300 m, the field is dominated by the Eighteen Degree Water (Worthington, 1959). In the main thermocline, the center of the subtropical gyre is near 34°N, 72°W. The main thermocline rises south and east of this point, indicative of the Gulf Stream recirculation gyre (Worthington, 1976).

TEMPERATURE AT 300 M.

LONGITUDE

LATITUDE

17

16

17·5

15

14

13

12

11

10

9

18·0

50° 60° 70° 80°

40° 30° 20°
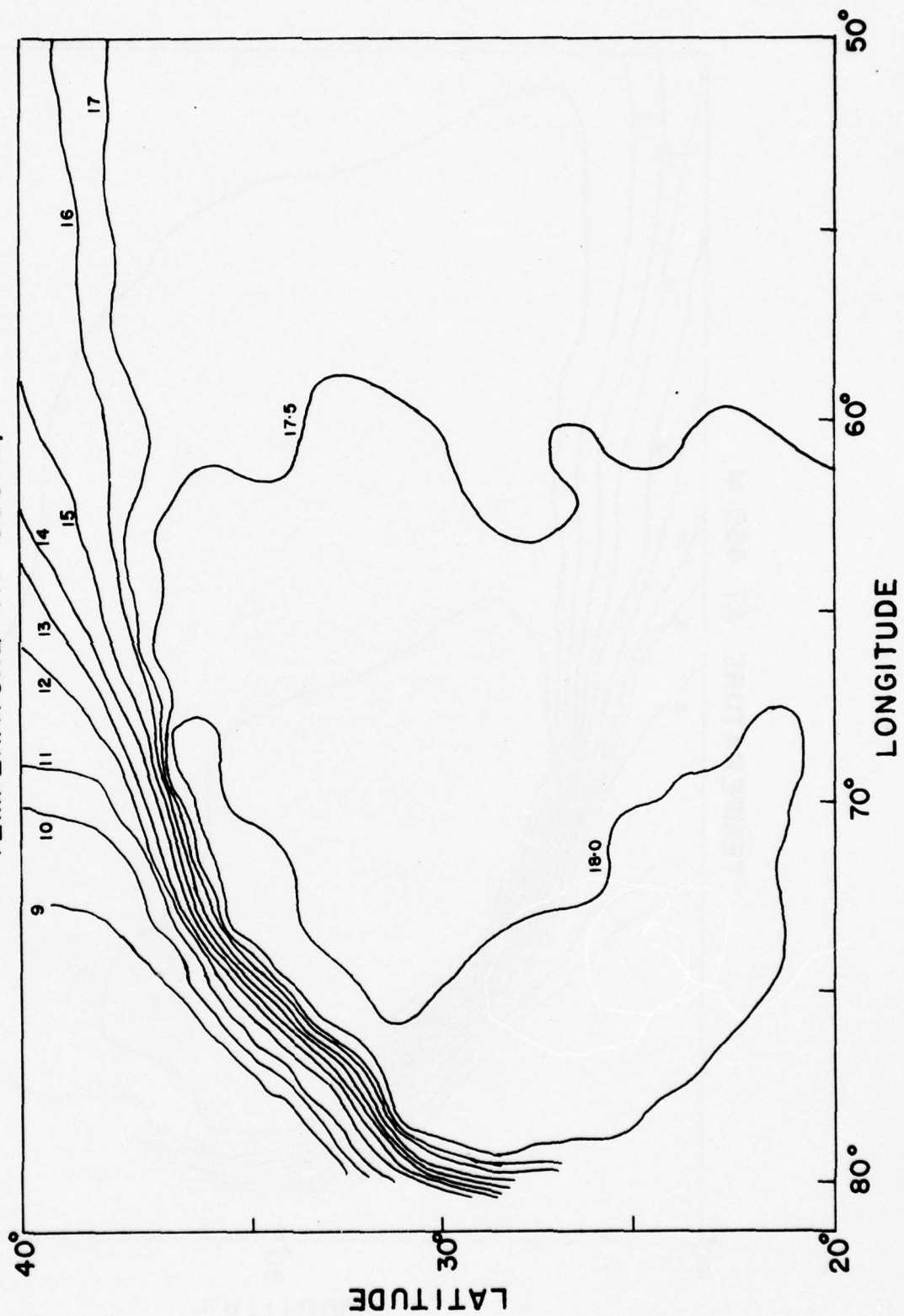
TEMPERATURE AT 450 M.
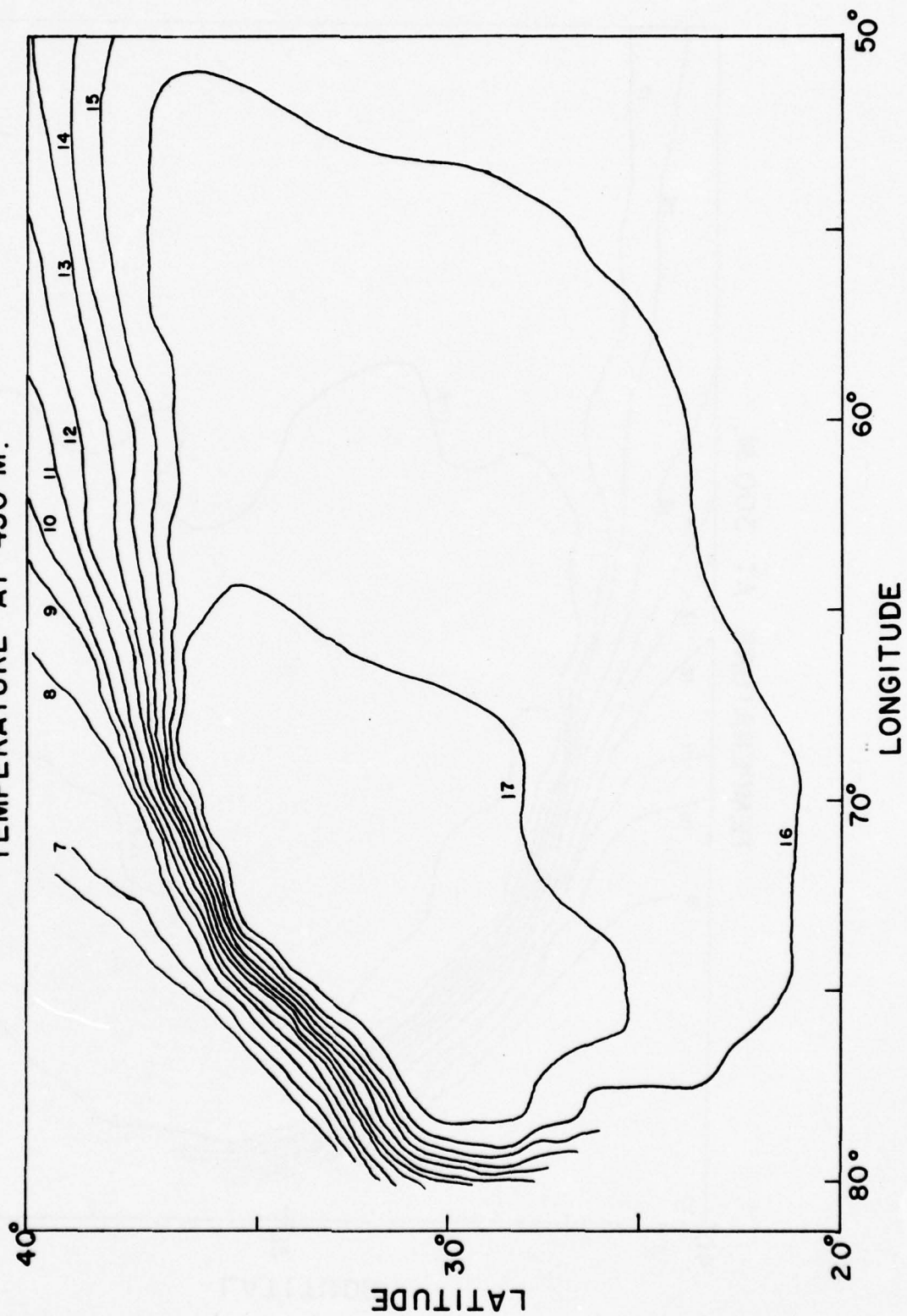
TEMPERATURE AT 700 M.

LONGITUDE

LATITUDE
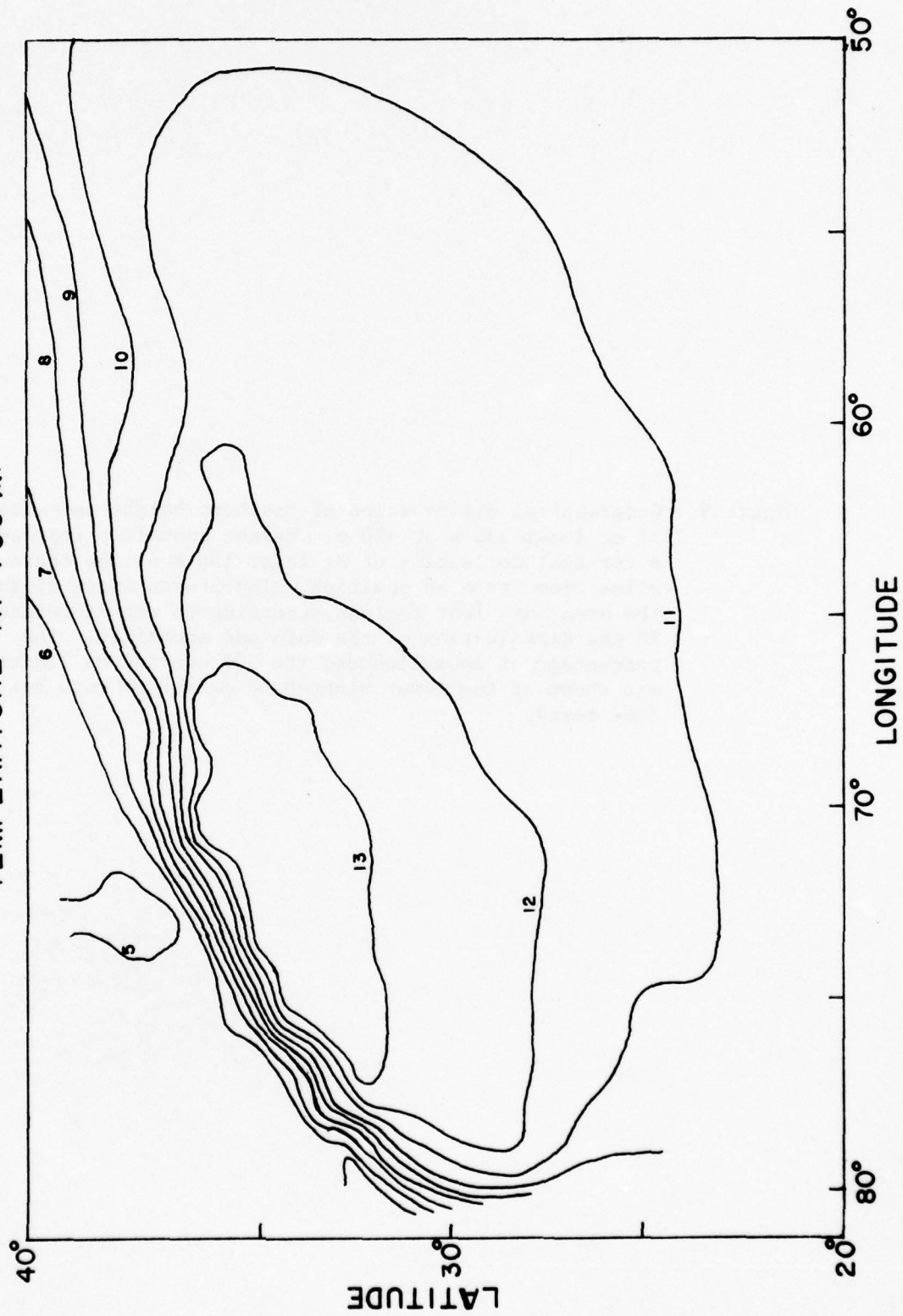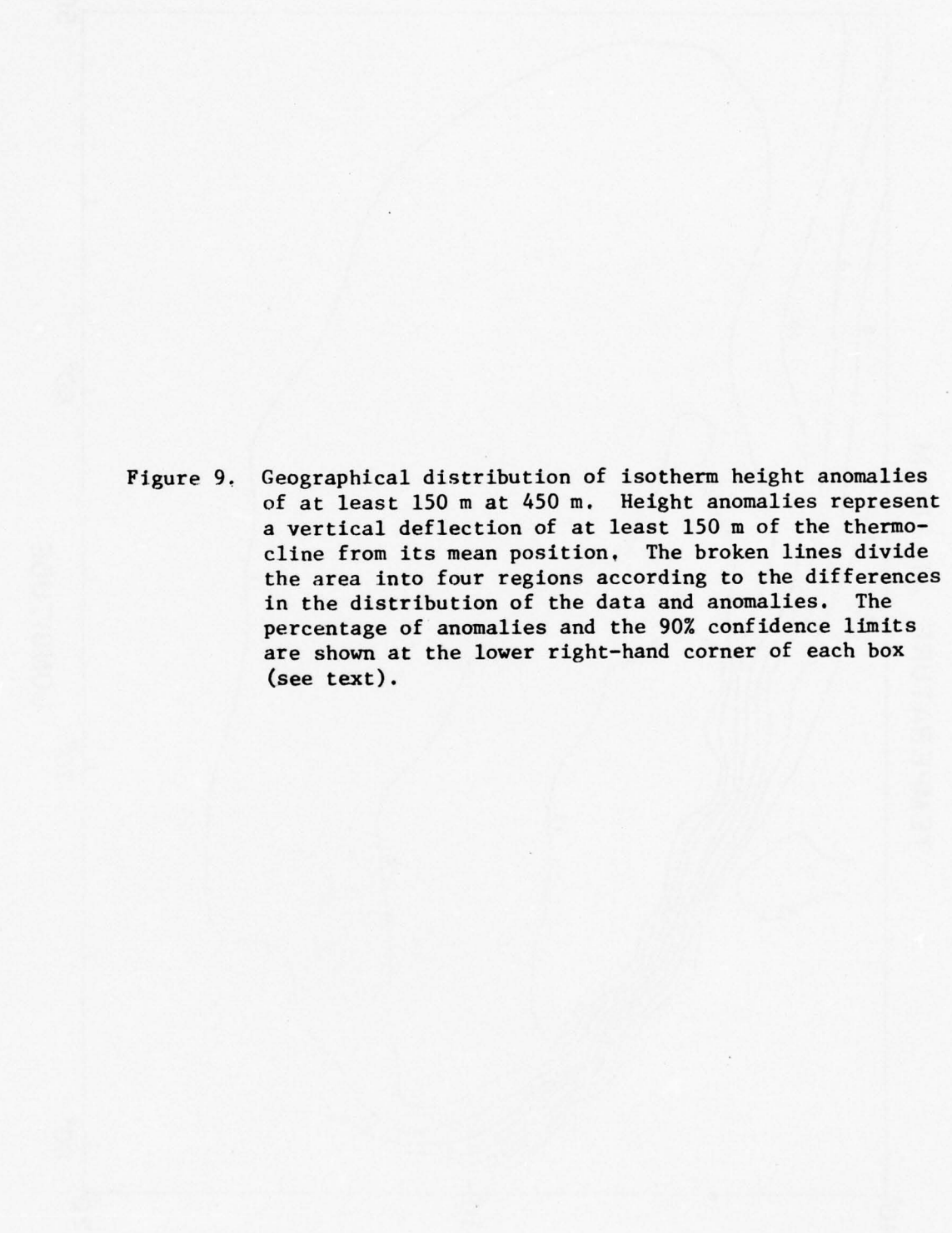
Figure 9. Geographical distribution of isotherm height anomalies
of at least 150 m at 450 m. Height anomalies represent
a vertical deflection of at least 150 m of the thermo-
cline from its mean position. The broken lines divide
the area into four regions according to the differences
in the distribution of the data and anomalies. The
percentage of anomalies and the 90% confidence limits
are shown at the lower right-hand corner of each box
(see text).

Figure 17. [caption text not legible]
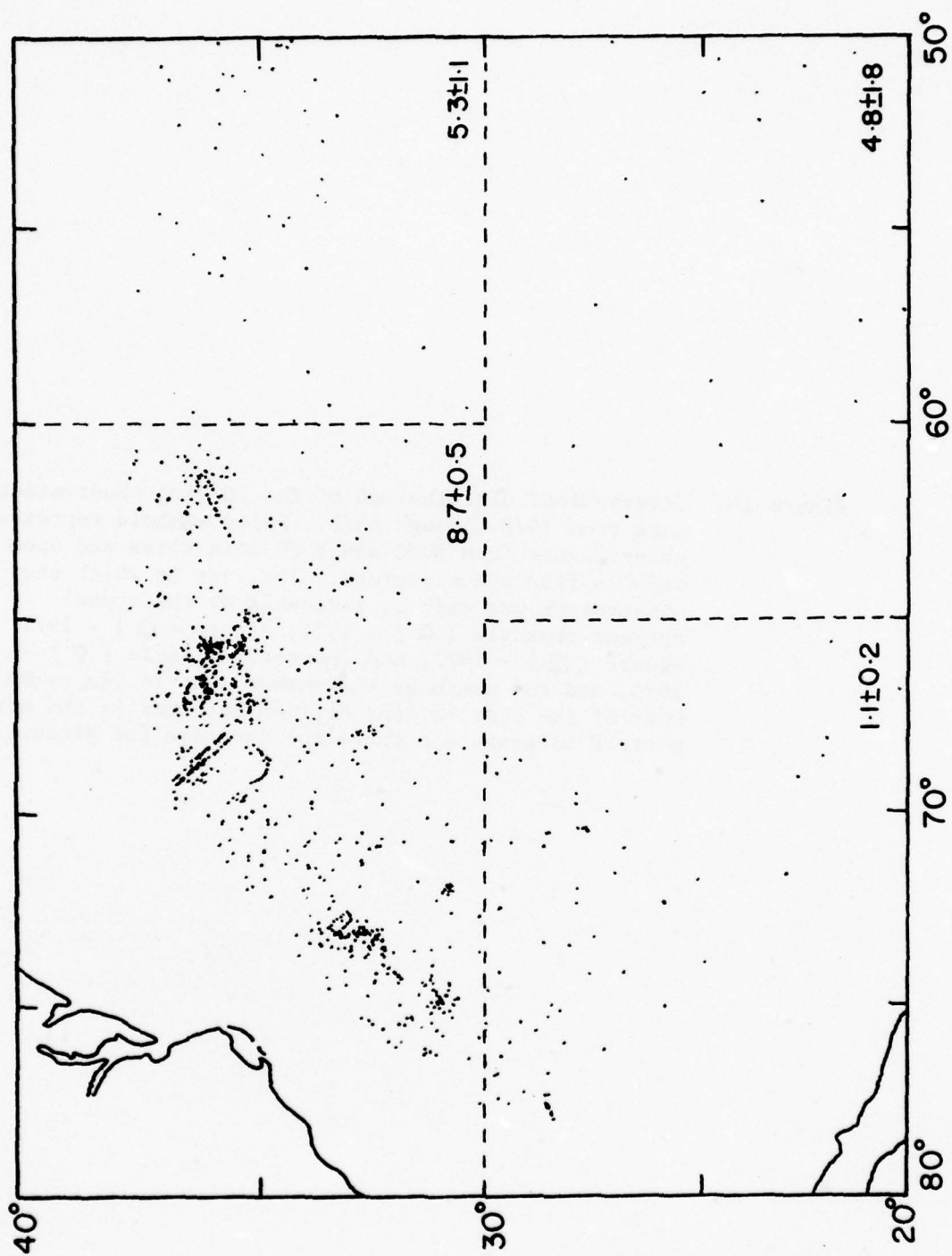
Figure 10. Geographical distribution of the 70 ring observations
made from 1970 through 1973. Solid symbols represent
observations from NODC and FNWC data files and open
symbols from other sources. The year in which the
observation was made is indicated by the symbol:
upright triangle (△) – 1970, circle (○) – 1971,
square (▢) – 1972, and inverted triangle (▽) –
1973, and the month by the number next to the symbol.
Most of the observations are concentrated in the north-
western Sargasso Sea where the data are the densest.
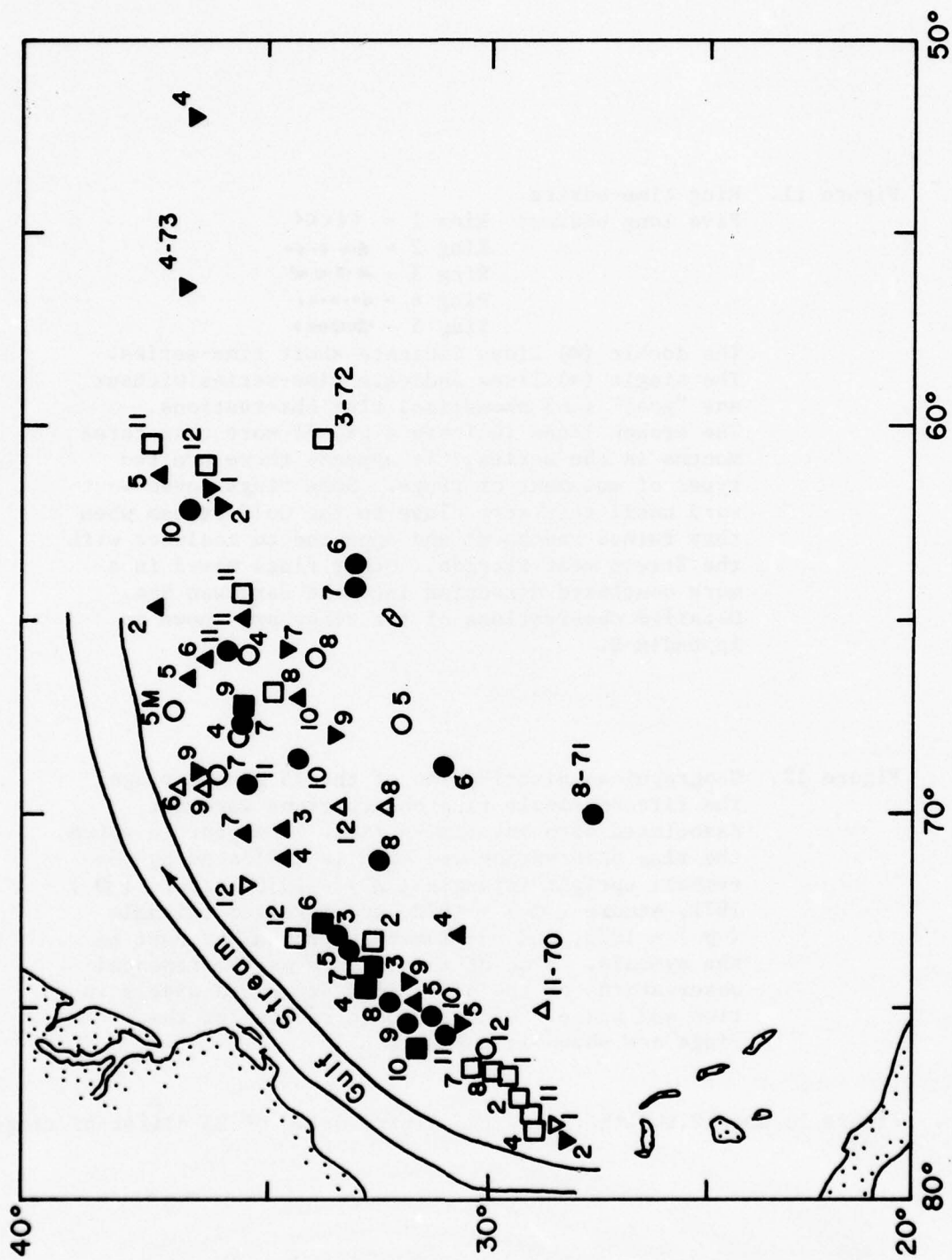
Figure 11.   Ring time-series.
              Five long series: Ring 1 – ⟨⟨⟨⟨⟨
                                  Ring 2 – ←←←←
                                  Ring 3 – ◀◀◀◀
                                  Ring 4 – ◀••••••
                                  Ring 5 – ◀ooooo
              The double (⇒) lines indicate short time-series.
              The single (→) lines indicate time-series without
              any "good" (≥3 anomalies) ring observations.
              The broken lines indicate a gap of more than three
              months in the series. It appears there are two
              types of movement of rings. Some rings moved west-
              ward until they were close to the Gulf Stream when
              they turned southwest and appeared to coalesce with
              the Stream near Florida. Other rings moved in a
              more southward direction into the Sargasso Sea.
              Detailed observations of the rings are shown in
              Appendix B.

Figure 12.   Geographical distribution of the 15 single rings.
              The fifteen single ring observations were not
              associated with any time-series. The year in which
              the ring observation was made is indicated by the
              symbol: upright triangle (▲) – 1970, circle (O) –
              1971, square (◻) – 1972, and inverted triangle
              (▽) – 1973, and the month by the number next to
              the symbols. Some of these rings may be repeated
              observations of the same rings separated widely in
              time and space. Detailed observations of the
              rings are shown in Appendix B.

Figure 11 and 12 together show the distribution of 23 different rings.

40°

30°

20°

50°   60°   70°   80°
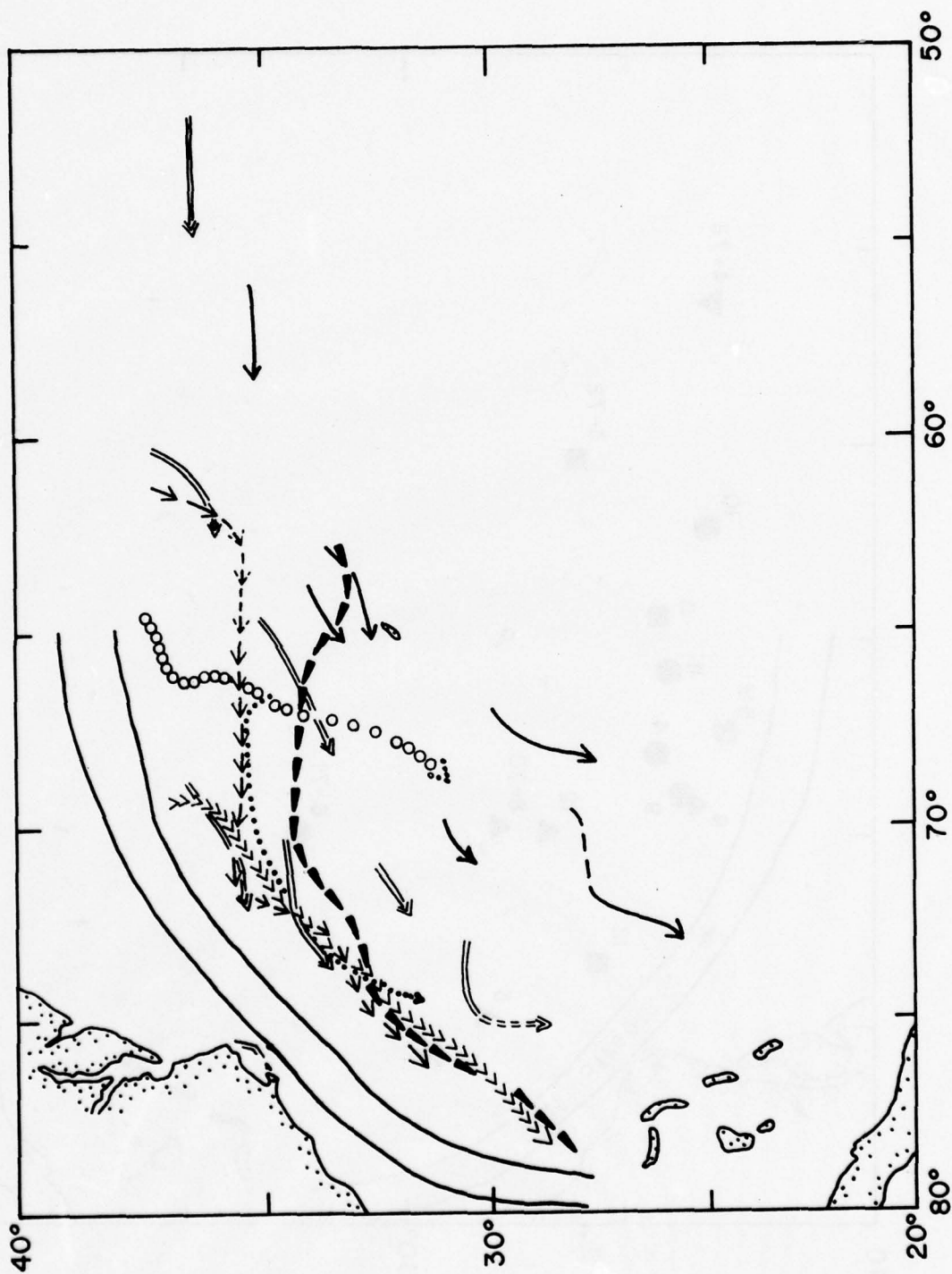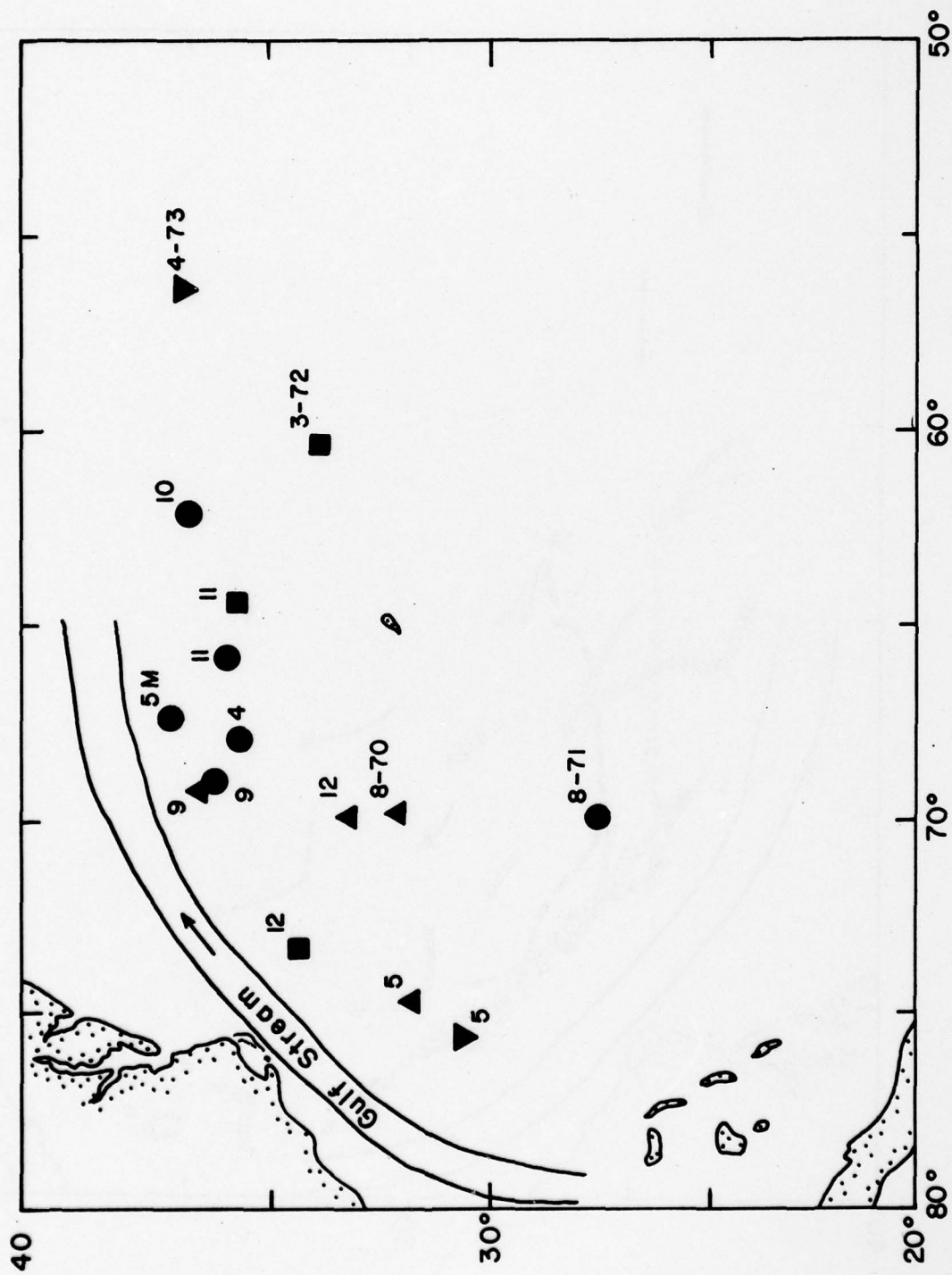
Figure 13. Frequency distribution of ring speed. Each speed
is estimated from the positions of adjacent ring
observations, sometimes rather subjectively,
especially when only one single anomaly was avail-
able. The mean speed is 2.7 km per day, with 82%
of the speeds between 1 to 4 km per day.
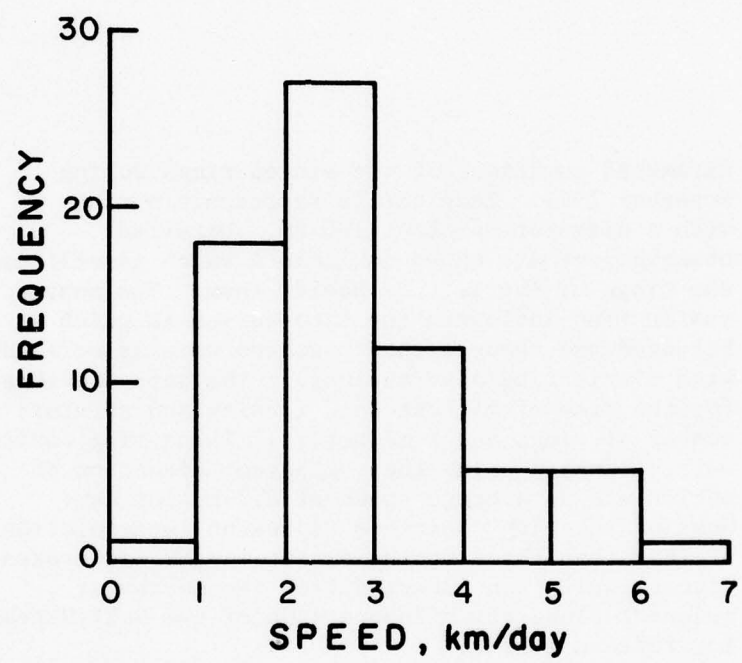
Figure 14. Estimated positions of the eleven rings during
            November 1971. Each circle represents a ring
            with a diameter of about 100 km. Detailed
            observations are shown in Table 4 which identifies
            the rings by the letters beside them. The number
            inside ring indicates the time-series in which it
            belonged and those without numbers were associated
            with single ring observations.   The date was chosen
            for the time of highest data density and greatest
            number of rings and time-series.   These ring positions
            were estimated using their apparent direction of
            motion and an average speed of 2.7 km per day.
            Most of the ring positions represent interpolation
            of less than three months except ring F (in broken
            circle) which was inferred from the southwest
            movement along the offshore side of the Gulf Stream
            for fifteen months.

Figure 11. Geographical distribution of the Sargasso Sea
solid station reference each within circle (a.b. report
1971). The multi-station are circuler 3, 10 count
those 5 station and the B-stations 5-9, and the run
means for cruise 768 across the A.
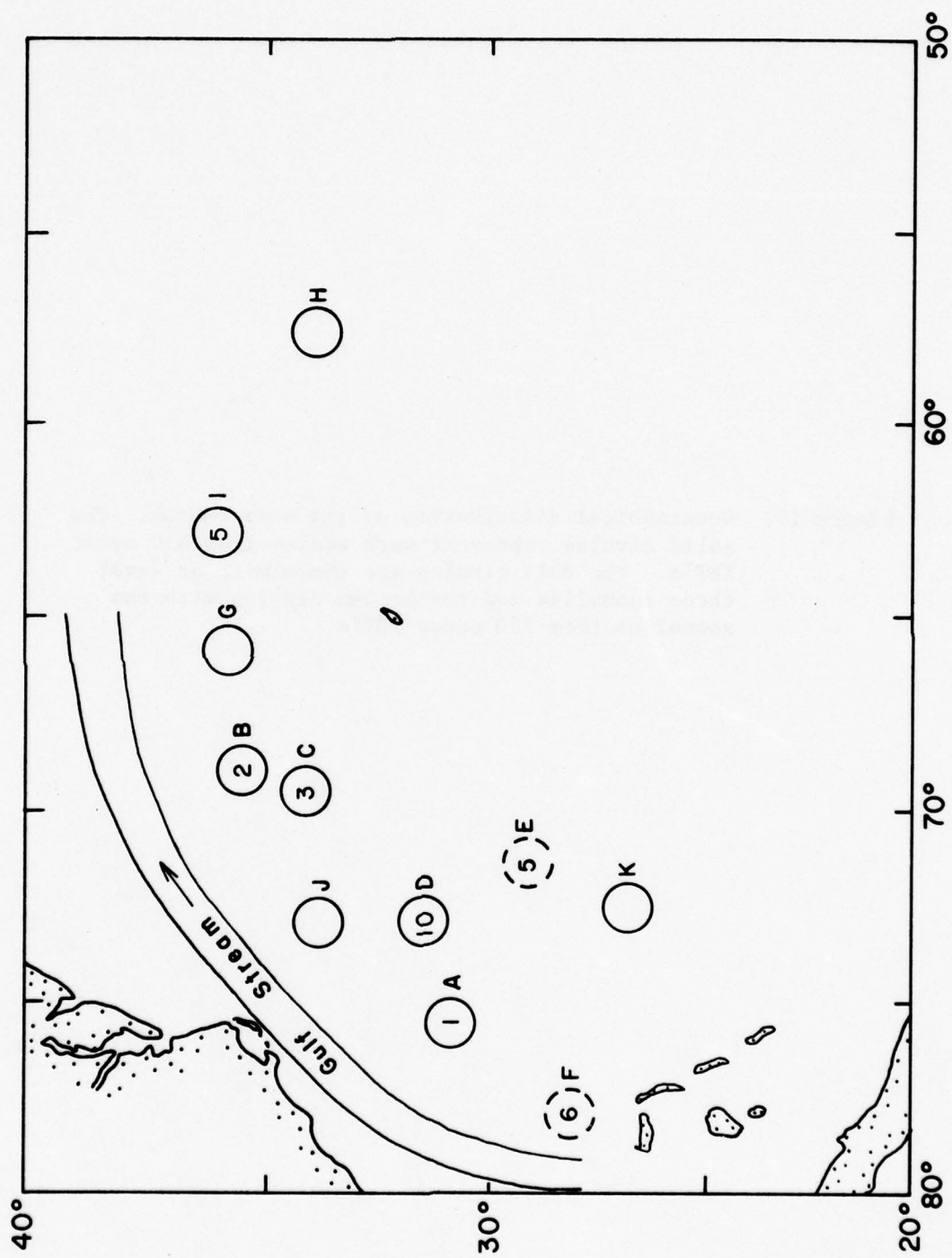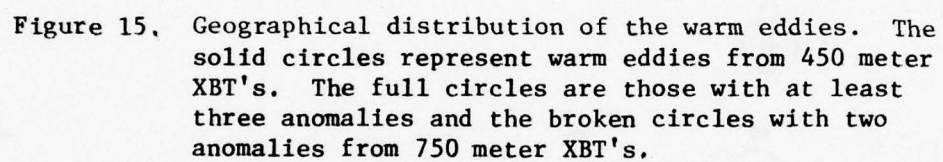
Figure 15. Geographical distribution of the warm eddies. The solid circles represent warm eddies from 450 meter XBT's. The full circles are those with at least three anomalies and the broken circles with two anomalies from 750 meter XBT's.
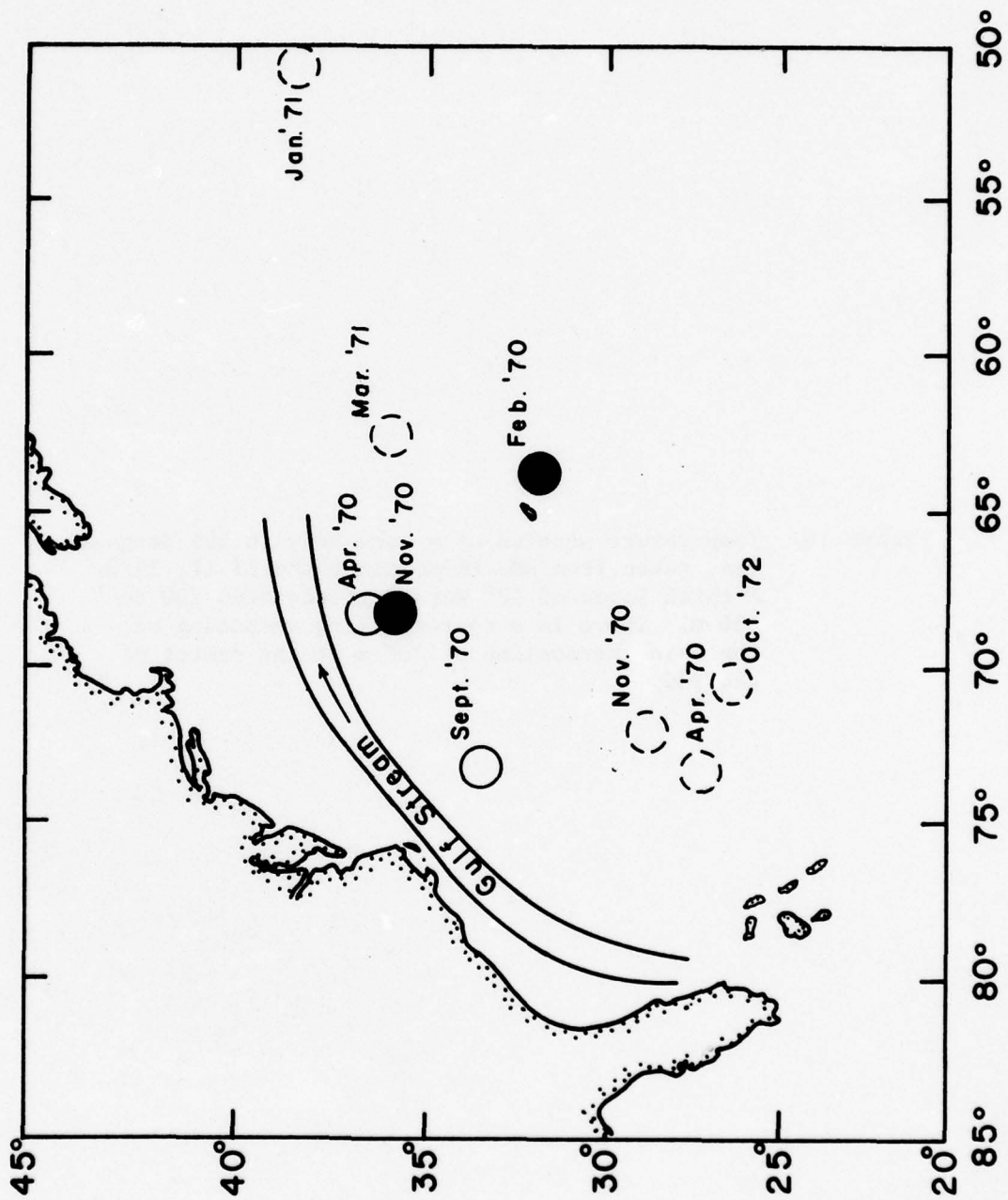
Figure 16. Temperature section of a warm eddy in the Sargasso
            Sea, taken from RMS FRANCONIA on April 17, 1970.
            A thick layer of 18° Water extends from 200 to
            600 m. There is a corresponding deepening of
            the main thermocline of 200 m at the center of
            the eddy.

DISTANCE FROM CENTER, km
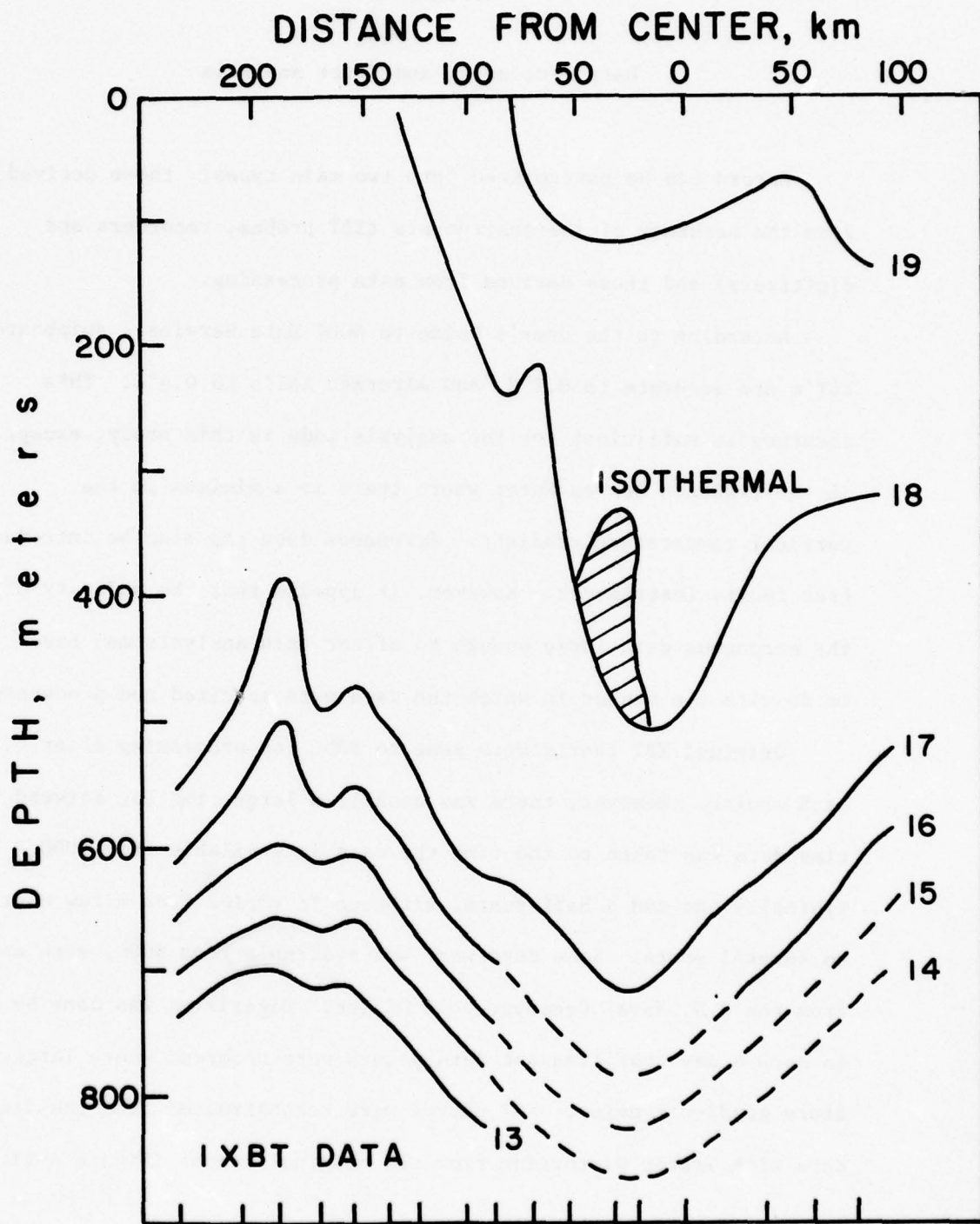
APPENDIX A

Data Processing and Error Analysis

Errors can be categorized into two main types: those derived from the accuracy of the instruments (XBT probes, recorders and digitizers) and those derived from data processing.

According to the User's Guide to NODC Data Services, shipboard XBT's are accurate to 0.1°C, and aircraft XBT's to 0.4°C. This accuracy is sufficient for the analysis made in this study, except in the Eighteen Degree Water where there is a minimum in the vertical temperature gradient. Erroneous data can also be introduced from faulty instruments. However, it appears that the majority of the erroneous data large enough to affect this analysis may have to do with the manner in which the data were acquired and processed.

Original XBT charts were sent to NODC for processing after each cruise. However, there was usually a large time lag between the time data was taken to the time the data is available from NODC, typically one and a half years, although it varies from a few months to several years. Some data were not available from NODC, such as those from the U.S. Naval Oceanographic Office. Digitizing was done by machines in such a way that frequent data points were recorded where large temperature gradients exist. XBT curves were reconstructed from the digitized data with little distortion from the original traces (Figure A-1). The

digitized data were stored on magnetic tapes and are available upon request to NODC.

The data processing scheme in FNWC varied considerably from that of NODC. Although some of the original XBT charts were digitized in the same manner as described above, a large number were digitized at sea and wired to FNWC. Points were read off at nonstandard and arbitrary intervals and sometimes the digitized data do not reflect details of the real XBT traces (Figure A-2). Further errors may be introduced by recording the wrong depths, temperatures, and even dates and positions.

It was very difficult in this study to be sure whether the anomalous features were real or consisted of erroneous data. Presumably data processors at NODC and FNWC have also had an equal difficulty in eliminating bad data. Extra precautions, some rather subjective, were used to offset the effect of bad data. The ring criterion of three anomalies was used to provide corroboration of the identification of a ring. Individual temperature profiles were checked for possible errors (incorrect positions, inversions, spikes) and those traces that looked suspicious were not used. Ring observations were checked by comparing them to non-anomalous observations; if there was a conflict, the ring observation was discarded.

Figure A-1.   Examples of XBT's from NODC. Traces were reconstructed
              from digitized values indicated by the small crosses.
              Digitization was done in such a way that frequent data
              points were recorded where a large temperature gradient
              existed. At the lower right-hand corner of each plot,
              the numbers indicate the code number of the XBT, the
              code of the ship, the year, month and day, the longi-
              tude and latitude at which the data was taken. Trace
              61400 was taken in the Sargasso Sea and trace 66805
              in a warm eddy. Due to the small temperature gradient
              in the extra thick layer of Eigtheen Degree Water, there
              are only four digitized points between 200 and 600 m in
              the trace taken in the warn eddy as compared with fifteen
              points in the one taken in the Sargasso Sea where larger
              temperature gradients exist at such depths.

TEMPERATURE IN C.

61400
31065M
70   1   21
27   0   N
74 32   M

DEPTH IN M.

TEMPERATURE IN C.

66805
31075F
70   4   17
35 13   N
67 46   M

DEPTH IN M.
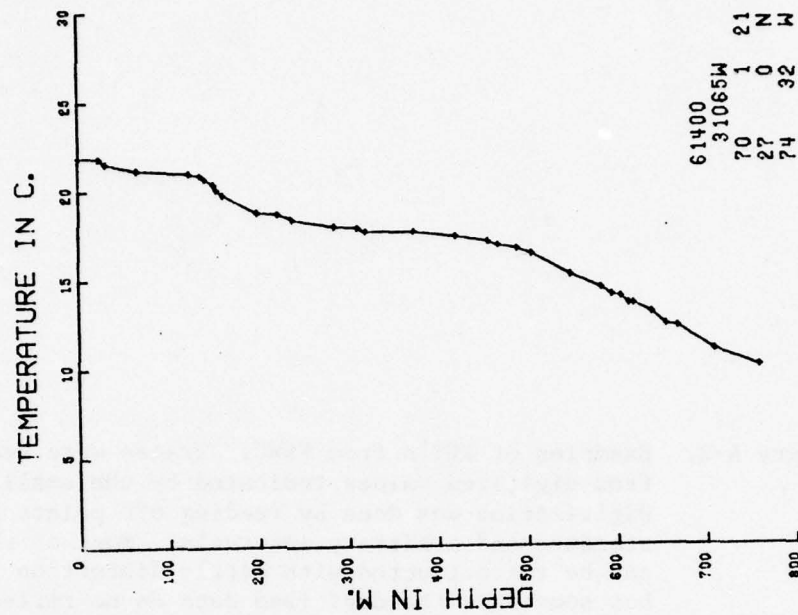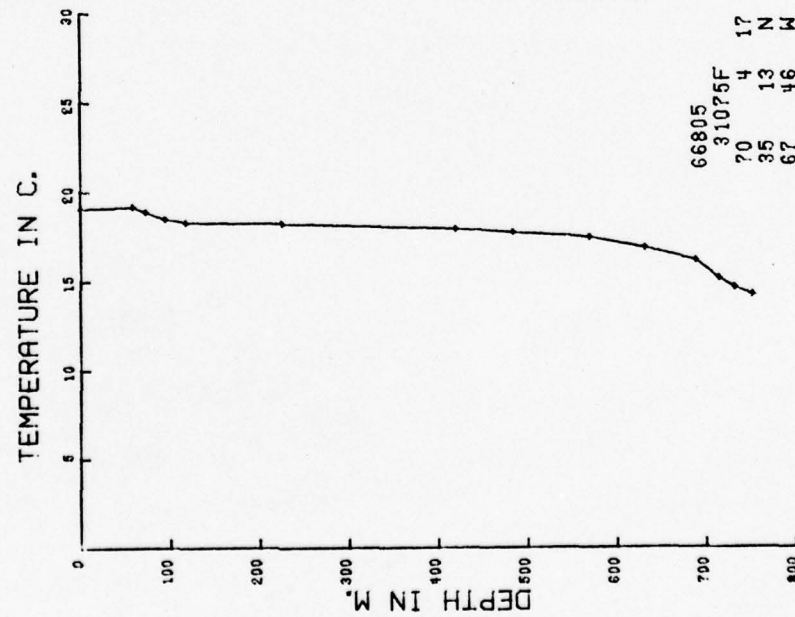
Figure A-2.   Examples of XBT's from FNWC, Traces were reconstructed
from digitized values indicated by the small crosses.
Digitization was done by reading off points at non-
standard and arbitrary intervals. Most of the traces
can be reconstructed with little distortion (trace 1081)
but sometimes the digitized data do no reflect details
of the real XBT traces due to insufficient points
(trace 6427).

TEMPERATURE IN C.
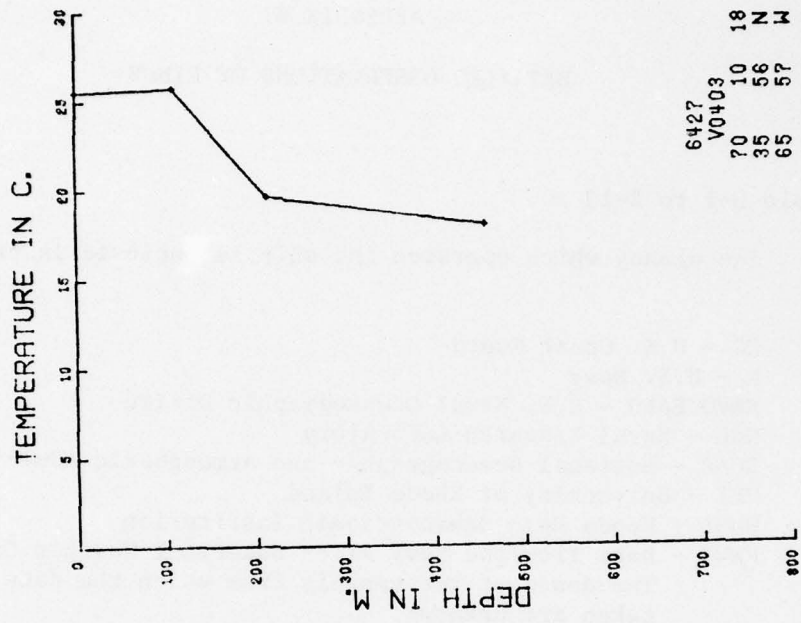
6427
V0403
70   10   18
35   56   N
65   57   M

DEPTH IN M.

TEMPERATURE IN C.

1081
VVVV
70   3   31
24   36   N
76   9   M

DEPTH IN M.
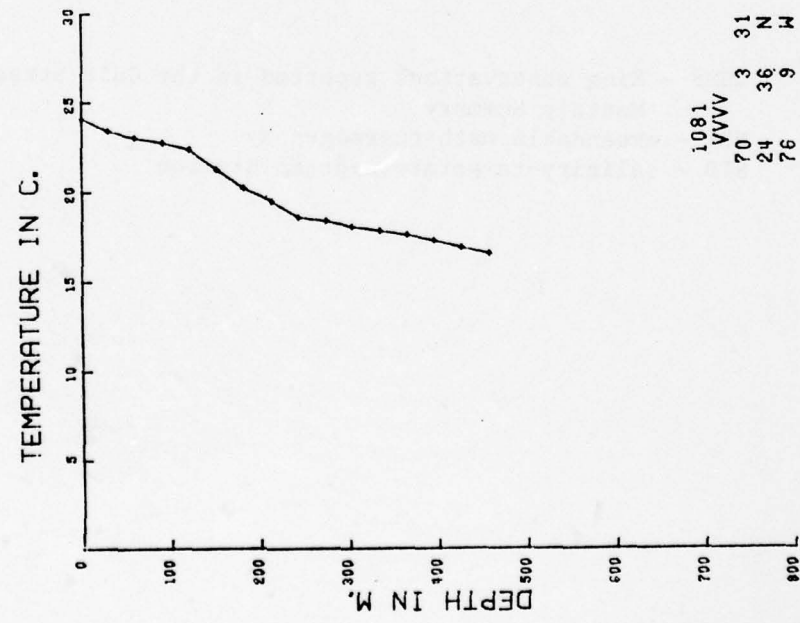
APPENDIX B

DETAILED OBSERVATIONS OF RINGS

Table B-1 to B-13

*   The agency which operates the ship is enclosed in parenthesis.

     CG - U.S. Coast Guard
     N - U.S. Navy
     NAVOCEANO - U.S. Naval Oceanographic Office
     NRL - Naval Research Laboratory
     NOAA - National Oceanographic and Atmospheric Administration
     URI - University of Rhode Island
     WHOI - Woods Hole Oceanographic Institution
     FNWC - Data from the Navy Fleet Numerical Weather Central.
            The names of the vessels from which the data were
            taken are unknown.

**   GSMS - Ring observations reported in the Gulf Stream
            Monthly Summary
     XBT - expendable bathythermography
     STD - salinity-temperature-depth station

TABLE B-1. <u>Observations of Ring 1.</u>

<u>Date</u>	<u>Platform/Agency</u>[*]	<u>Observations</u>[**]
<u>1970</u>		
June 1	Franconia (NAVOCEANO)	reported in GSMS
June 12, 18	Vogue (N), FNWC	2 XBT's
July 18	Rockaway (CG)	2 STD's, 1 hydrostation
August 18	FNWC	1 XBT
<u>1971</u>		
March 23	Ingham (CG), FNWC	6 XBT's
April 12-14		satellite data
May 12		satellite data
May 10, 11, 18	Trident (URI)	65 XBT's, 3 hydrostations
June 1		satellite data
July 16, 25	FNWC	2 XBT's
August 4,20,28	FNWC	3 XBT's
September 20,26,29	Little Rock (N)	3 XBT's
October 21-24	Trident (URI)	28 XBT's, 5 STD's
November 5,9,14	Sumner (N), FNWC	3 XBT's
December 10	Kane (NAVOCEANO)	3 XBT's
<u>1972</u>		
January 8	Wilkes (NAVOCEANO)	10 XBT's
January 19	Evergreen (CG)	2 XBT's
February 19	Mizar (NRL)	17 XBT's
March 3	Bordelon (N)	2 XBT's
April 8,9	Researcher (NOAA)	22 XBT's

TABLE B-2. <u>Observations of Ring 2.</u>

<u>1970</u>		
May 1,14,15	F. Sherman (N)	3 XBT's
July 20	Rockaway (CG)	1 STD, 1 hydrostation
October 30,31	Cromwall, Evergreen (N)	8 XBT's
<u>1971</u>		
April 2		reported in GSMS
April 18	Cromwall (N)	2 XBT's
July 22,25,26,29	E. McDonald, Browning	16 XBT's
September 29	FNWC	1 XBT
November 7	Lynch (NAVOCEANO)	15 XBT's
<u>1972</u>		
January 6	FNWC	1 XBT
February 28	FNWC	1 XBT
June 8,13	W.H. Standley (N)	3 XBT's, satellite data
July 27	FNWC	1 XBT, satellite data
August 8,14	FNWC	2 XBT's
October 25	X.D. Yarnel (N)	3 XBT's

TABLE B-3. <u>Observations of Ring 3.</u>

<u>Date</u>	<u>Platform/Agency</u>*	<u>Observations</u>**
<u>1971</u>		
May 8	Norwalk (N)	1 XBT
June 16, 17	Ingham (N)	3 XBT's
June 25, July 8	J. Daniels	4 XBT's
July 22	FNWC	1 XBT
August 29,30		reported in GSMS
September 21	FNWC	1 XBT
October 20,22,23	Steinaker (N)	4 XBT's
December 16	J. Daniels (N)	1 XBT
<u>1972</u>		
February 15,25	FNWC	2 XBT's, in GSMS
February 28		
March 1,3,8	Blandy (N)	6 XBT's
April 27	Garcia (N), Knorr (NOAA)	9 XBT's
June 17	FNWC	1 XBT
July		satellite data
August		satellite data
December	Trident (URI)	7 XBT's
<u>1973</u>		
January		satellite data
January 30,31		
February 4,6	Albatross IV (CG)	9 XBT's

TABLE B-4. <u>Observations of Ring 4.</u>

<u>1972</u>		
August 13		reported in GSMS
September 23	Atlantis II (WHOI)	26 XBT's
November 7	Chain (WHOI)	1 XBT
<u>1973</u>		
February 8	X.D. Yarnell (N)	1 XBT
March 7	Koelsch (N)	2 XBT's
April 5,15	Whiting (N)	2 XBT's
June 5,6	Morton (N)	2 XBT's
July 11,17	FNWC	2 XBT's
August 14	FNWC	1 XBT
September 14,17	FNWC	3 XBT's

TABLE B-5. Observations of Ring 5.

Date	Platform/Agency[*]	Observations[**]
1970		
February 28	Koelsch, McCloy Vogue (N)	8 XBT's
May 20-24	Vogue, Koelsch (N)	109 XBT's
June 10-18	Koelsch, Mc Cloy, Vogue (N)	107 XBT's
October 22,23	Intrepid (N)	12 XBT's
1971		
May		
June 20,21,28	J. Daniels (N)	3 XBT's

TABLE B-6. Observations of Ring 6.

1970		
March 1,7	Chain (WHOI)	2 STD's, 1 hydrostation
April 27,28	Atlantis II (WHOI)	4 XBT's
May 16,19	FNWC	1 hydrostations, 1 XBT
July 3,12	Victor (N)	2 XBT's
August 6	FNWC	1 XBT

TABLE B-7. Observations of Ring 7.

1972		
November 8		reported in GSMS
December 8		reported in GSMS
1973		
January 14-19	Lynch (NAVOCEANO)	25 XBT's
February 5-13	Lynch (NAVOCEANO)	14 XBT's

TABLE B-8. Observations of Ring 8.

1970		
April 27	Atlantis II (WHOI)	1 STD
June 27	C.R. Ware (N)	1 XBT
November	Androscoggin (CG)	Several STD's

TABLE B-9. <u>Observations of Ring 9.</u>

<u>Date</u>	<u>Platform/Agency</u>[*]	<u>Observations</u>[**]
<u>1973</u>		
June 7	FNWC	1 XBT
July 20	Ambassador (NAVOCEANO)	6 XBT's
September 8.11	FNWC	13 XBT's

TABLE B-10. <u>Observations of Ring 10.</u>

<u>1971</u>		
August 20,24,31	Norwalk (N), FNWC	2 XBT's, 3 STD's
September 13	FNWC	1 XBT
October 19	FNWC	1 XBT

TABLE B-11. <u>Observations of Ring 11.</u>

<u>1973</u>		
August 31	Ambassador (NAVOCEANO)	30 XBT's
September 9,14		
October 7,19	FNWC	2 XBT's
November 27,28		reported in GSMS

TABLE B-12. <u>Observations of Ring 12.</u>

<u>1973</u>		
April 14	FNWC	3 XBT's
May 22, 29	Morton (N)	2 XBT's
July 21,22	FNWC	1 XBT

TABLE B-13. Observations of Single Rings

Date	Platform/Agency[*]	Observations[**]
1970, September 27		reported in GSMS
1970, May 5,6,13	Tsxin, X.D.Yarnell (N)	4 XBT's
1970, August	Absecon (CG)	several STD's
1970, December	Chincoteague (CG)	several STD's
1971, April 25,26,30	Franconia (NAVOCEANO)	reported in GSMS
1971, May 24	Franconia (NAVOCEANO)	reported in GSMS
1971, September 17,18	Franconia (NAVOCEANO)	reported in GSMS
1971, September 30 October 2	FNWC	6 XBT's
1971, November 14	Lynch (NAVOCEANO)	5 XBT's
1971, August 14-17	Sims (N)	8 XBT's
1972, March 2,3	Chain (WHOI)	5 XBT's
1972, November 6		reported in GSMS
1972, December	Trident (URI)	
1973, April 13,21	Morton (N)	4 XBT's
1973, May 28,31	FNWC	3 XBT's

Figure B-1 to B-7.
        The observed positions of the ring time-series.
        The shaded circles indicate ring observations
        of at least three anomalies. Question marks
        indicate data gaps of more than three months.
        Figure B-7 shows the ring time-series which consist
        of ring observations only with one or two anomalies.
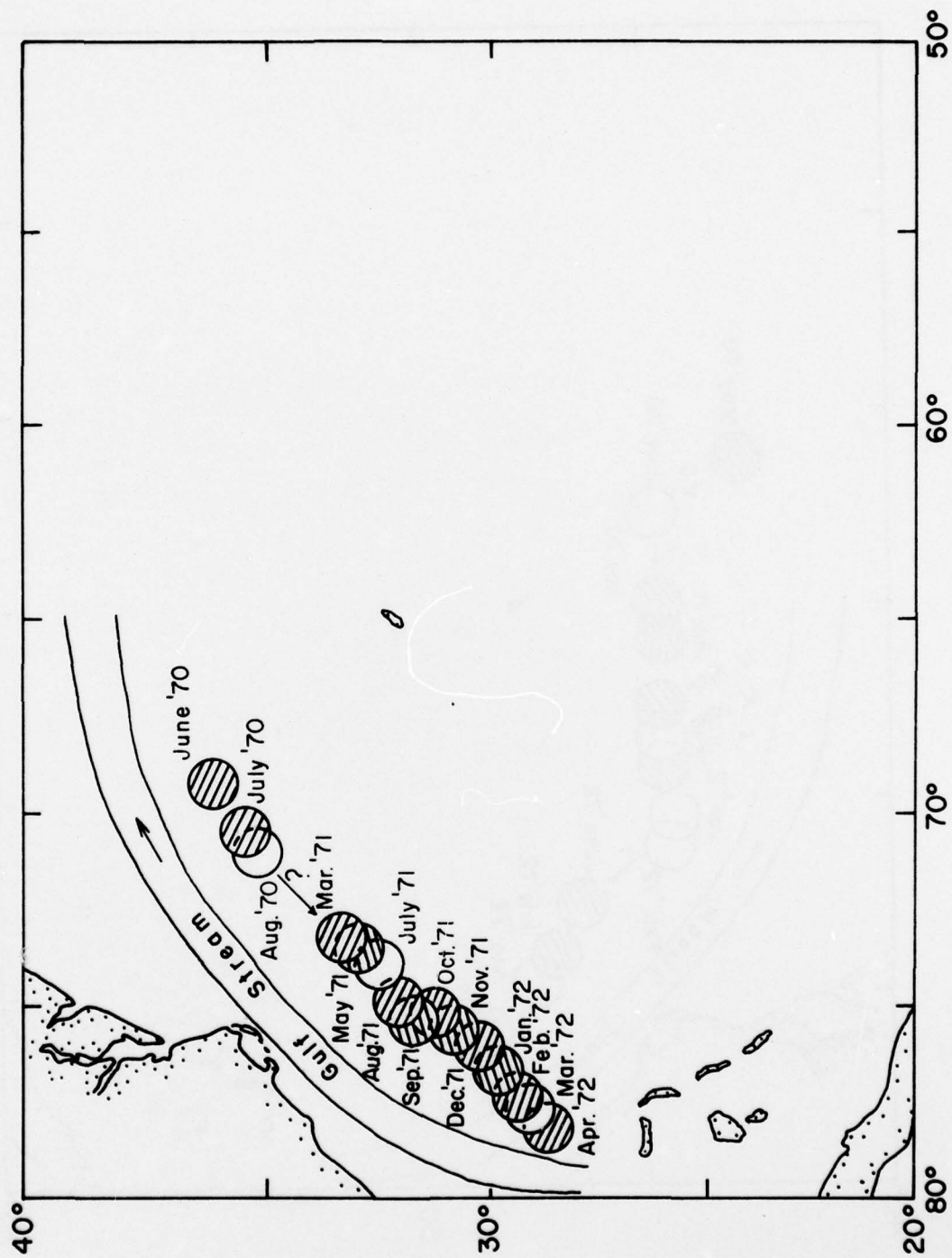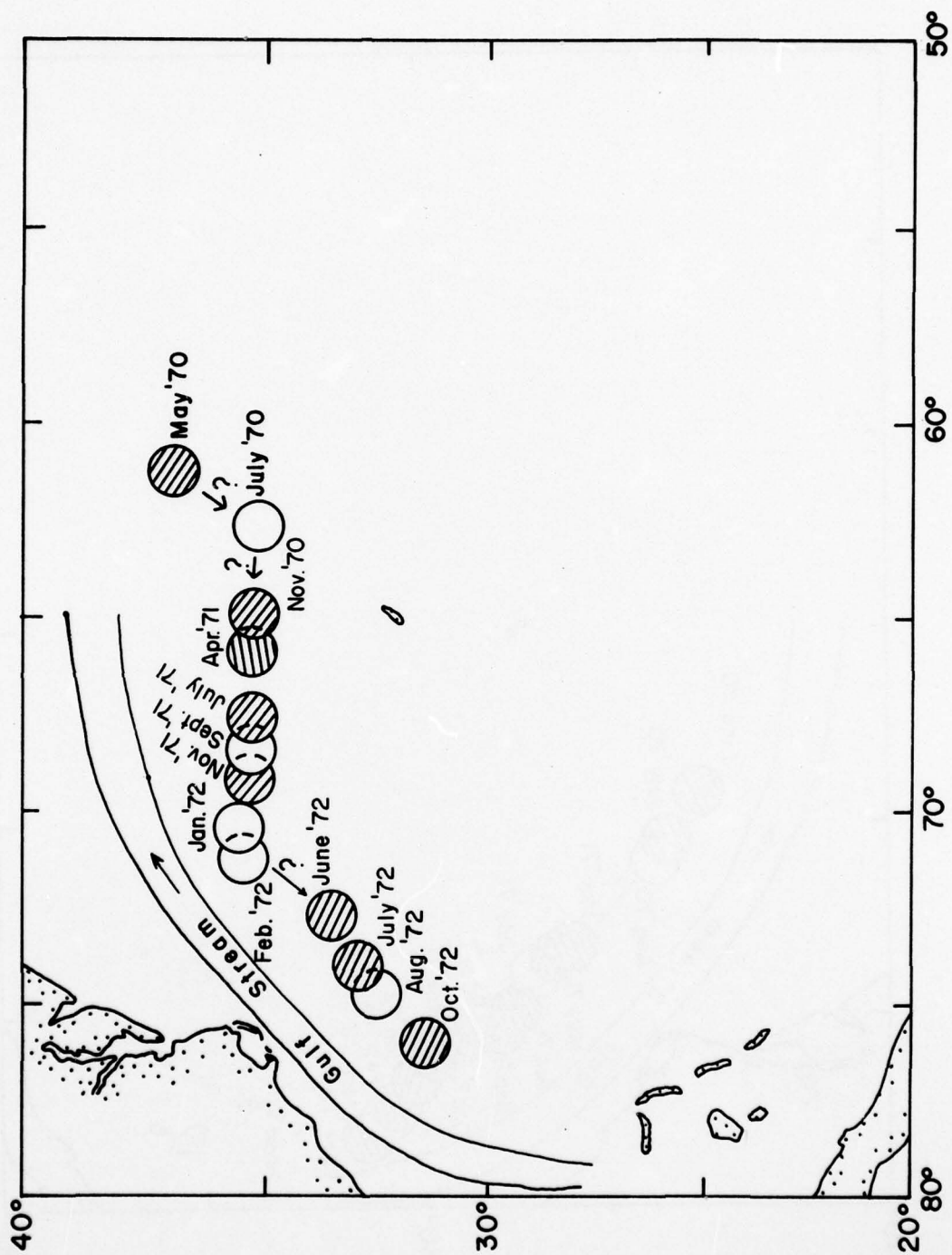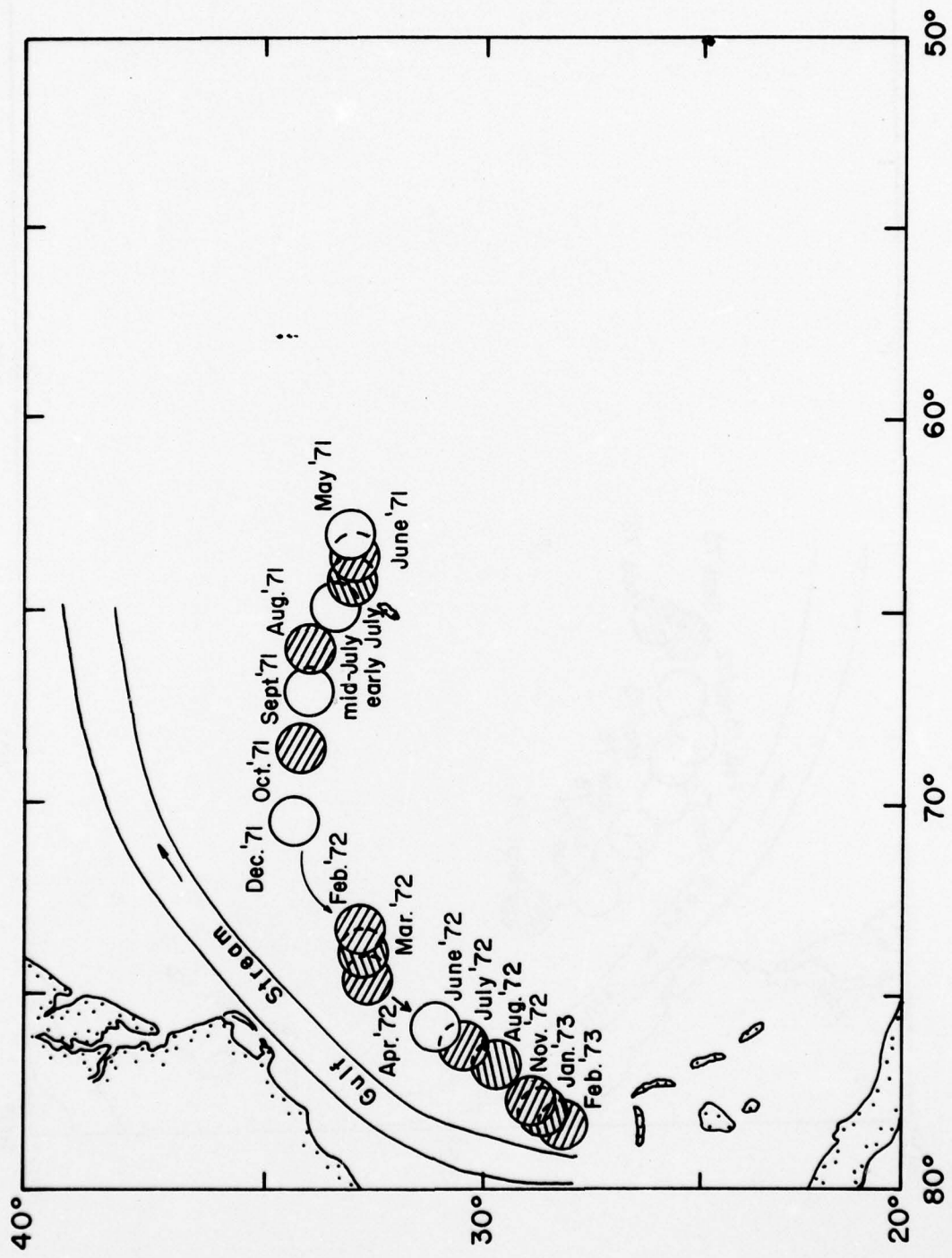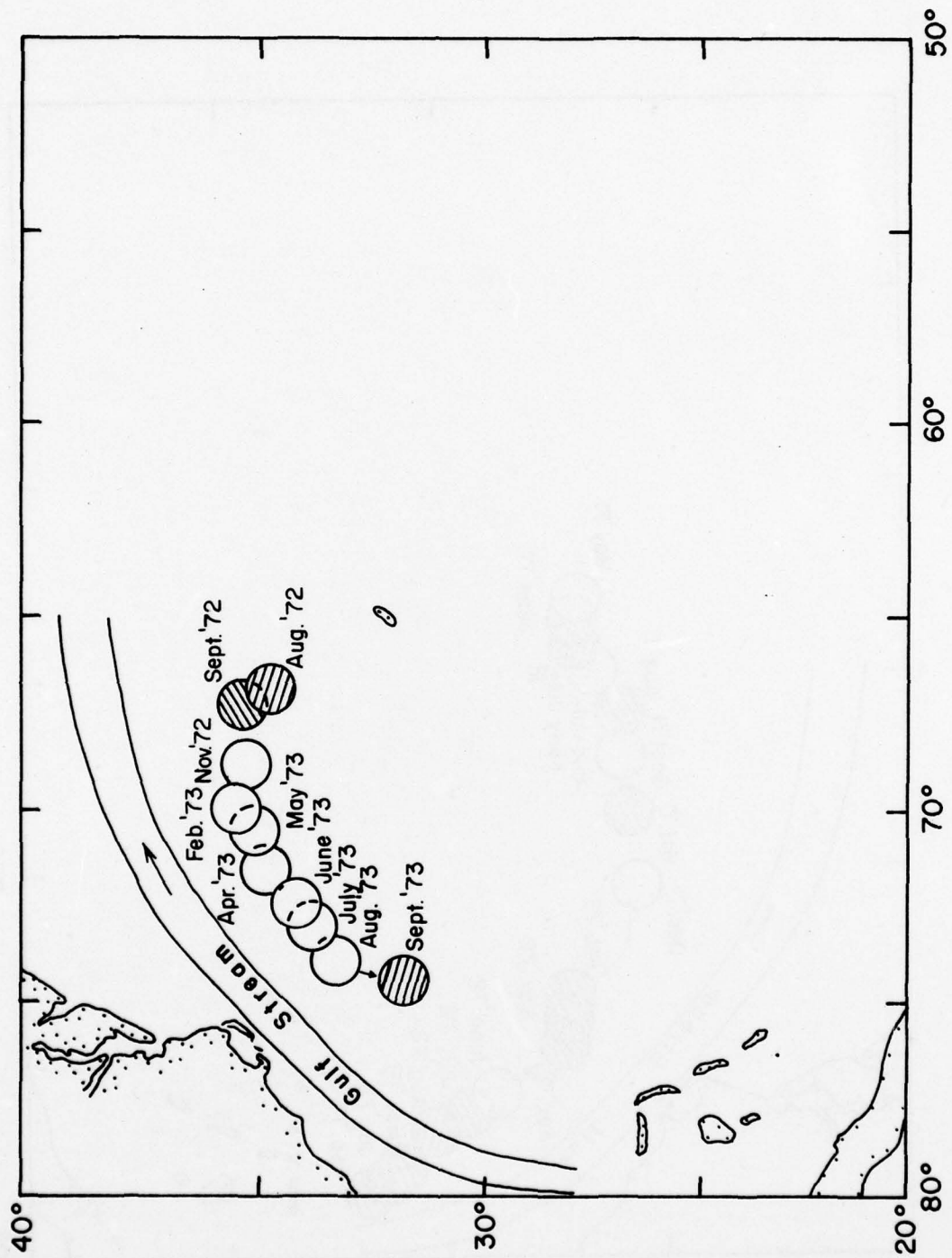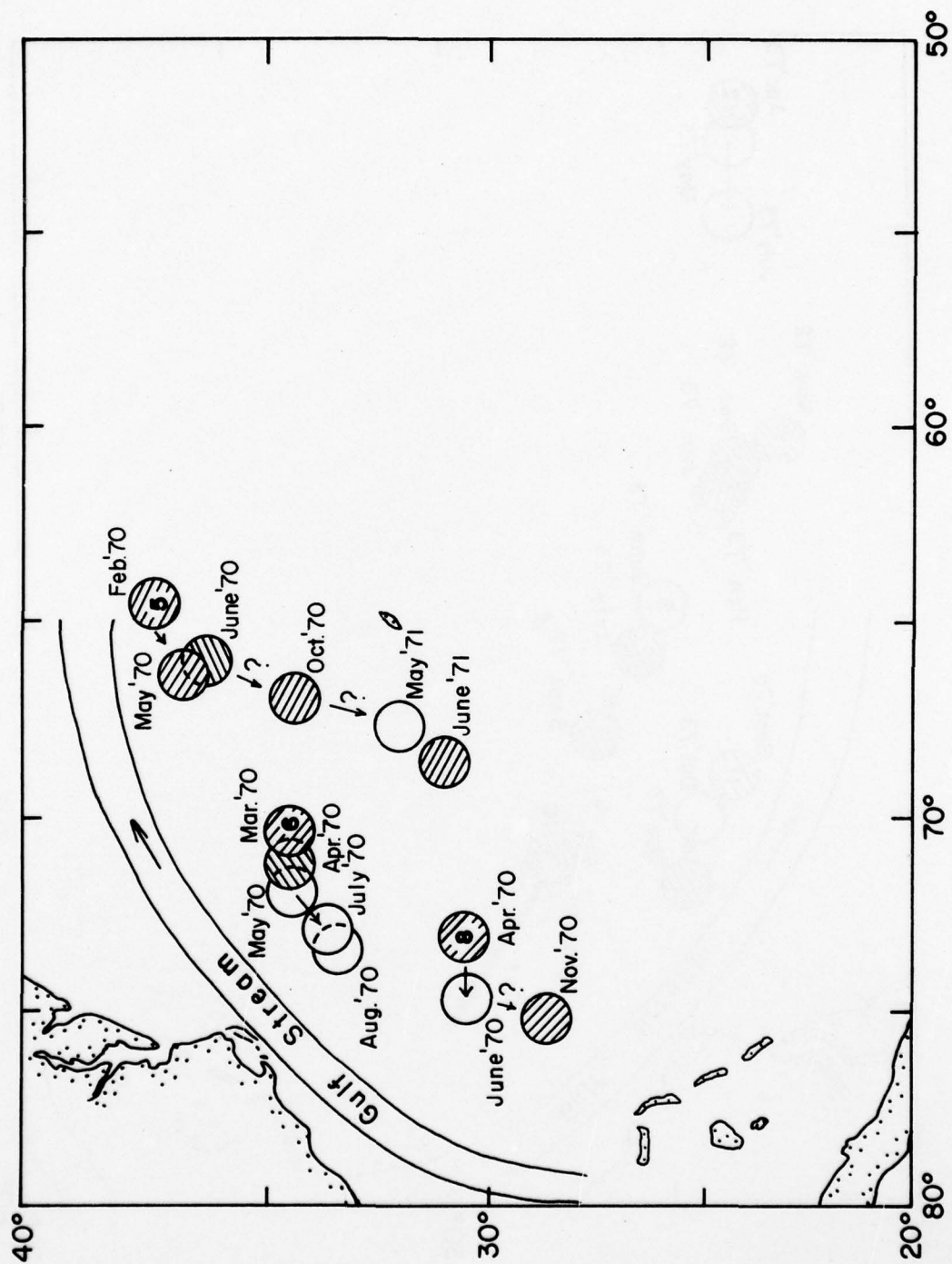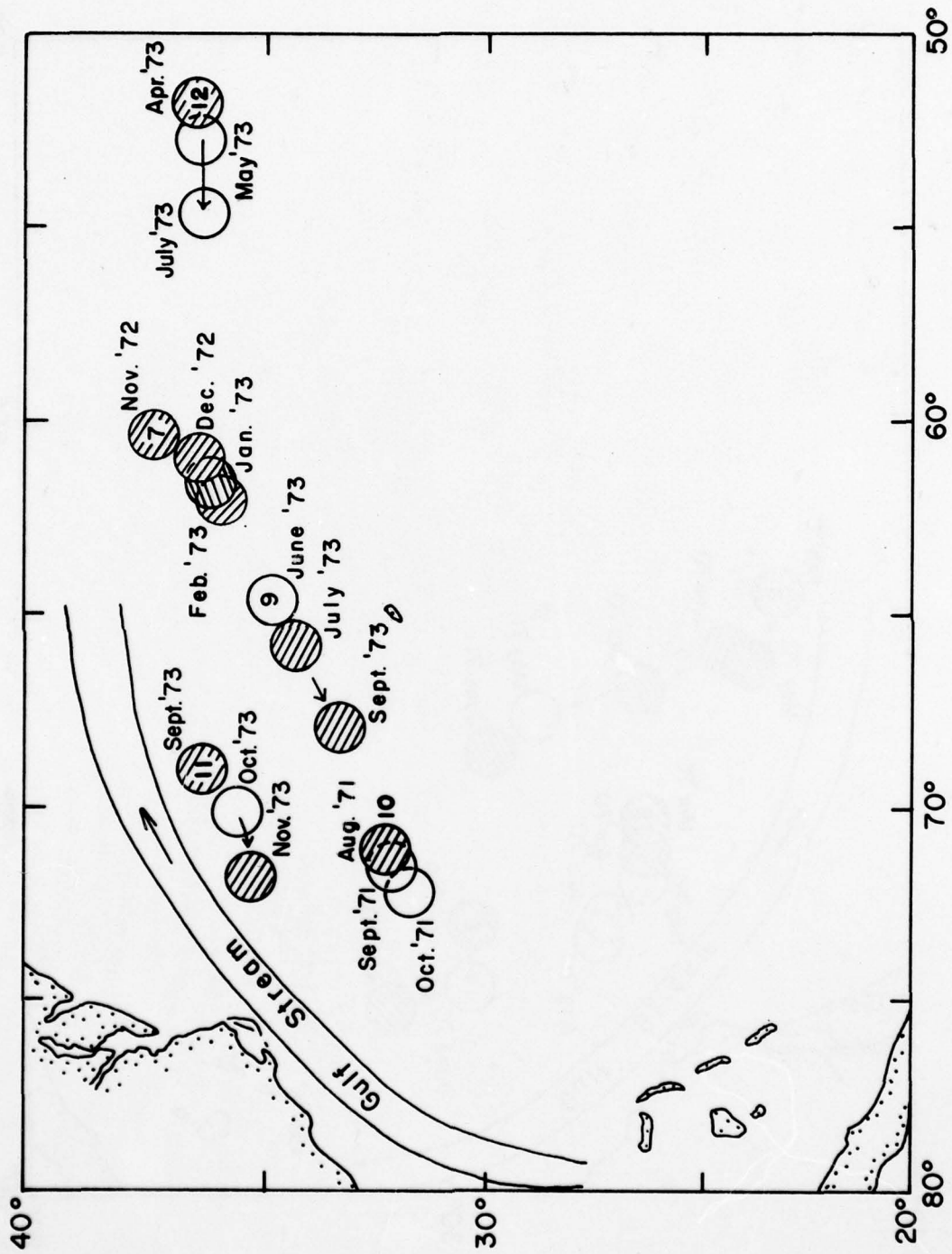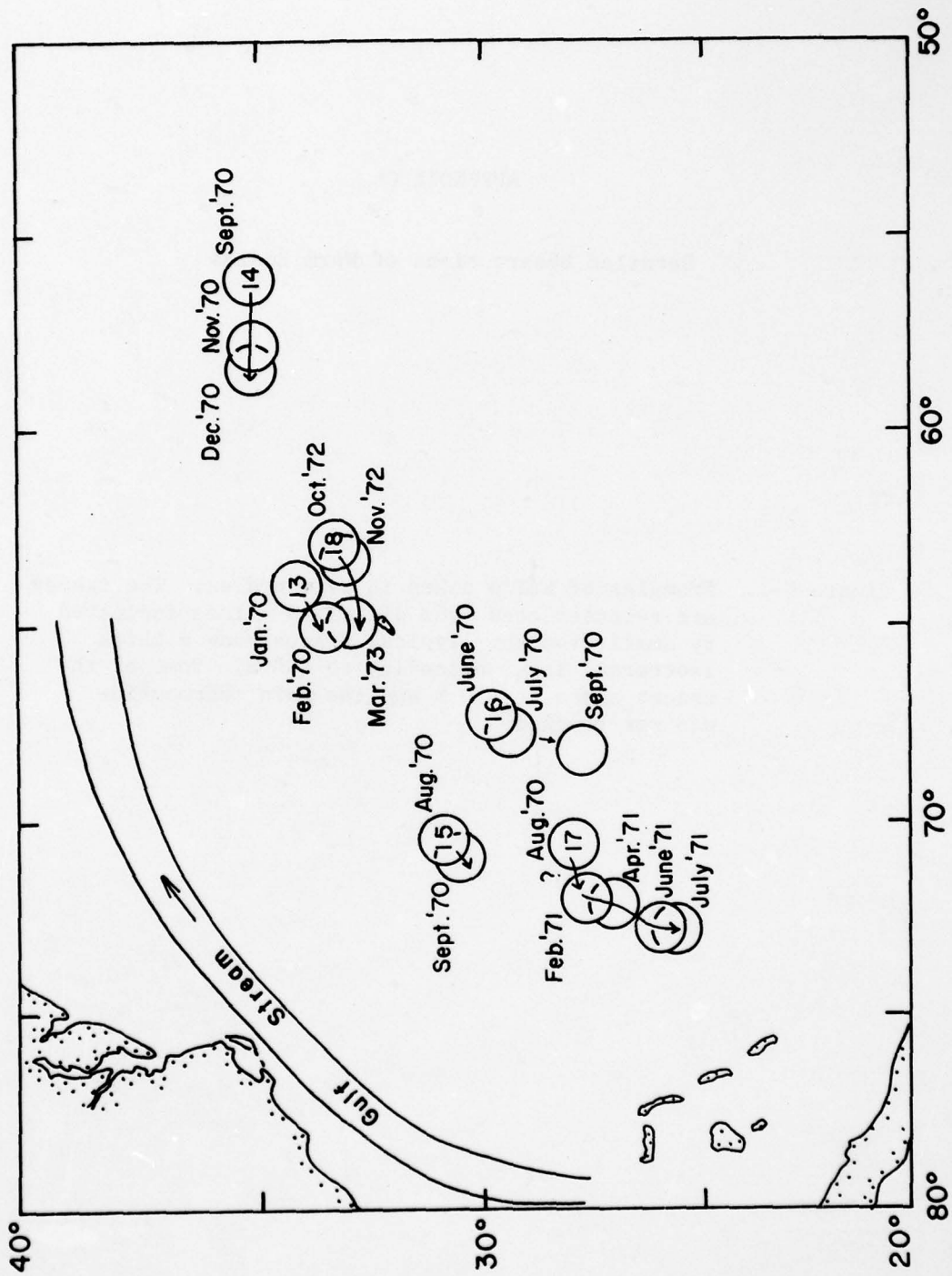
Gulf Stream

June '70
July '70
Aug. '70
Mar. '71
May '71
July '71
Aug. '71
Oct. '71
Sep. '71
Nov. '71
Dec. '71
Jan. '72
Feb. '72
Mar. '72
Apr. '72

40°

30°

20°

80°

70°

60°

50°

May '70

July '70

Nov. '70

Apr. '71

July '71

Sept. '71

Nov. '71

Jan. '72

Feb. '72

June '72

July '72

Aug. '72

Oct. '72

Gulf Stream

40°

30°

20°

50°

60°

70°

80°

Dec.'71 Oct.'71 Sept.'71 Aug.'71 May '71

Gulf

Stream

Feb.'72

Mar.'72

Apr.'72

June '72

July '72

Aug.'72

Nov.'72

Jan.'73

Feb.'73

mid-July

early July

June '71
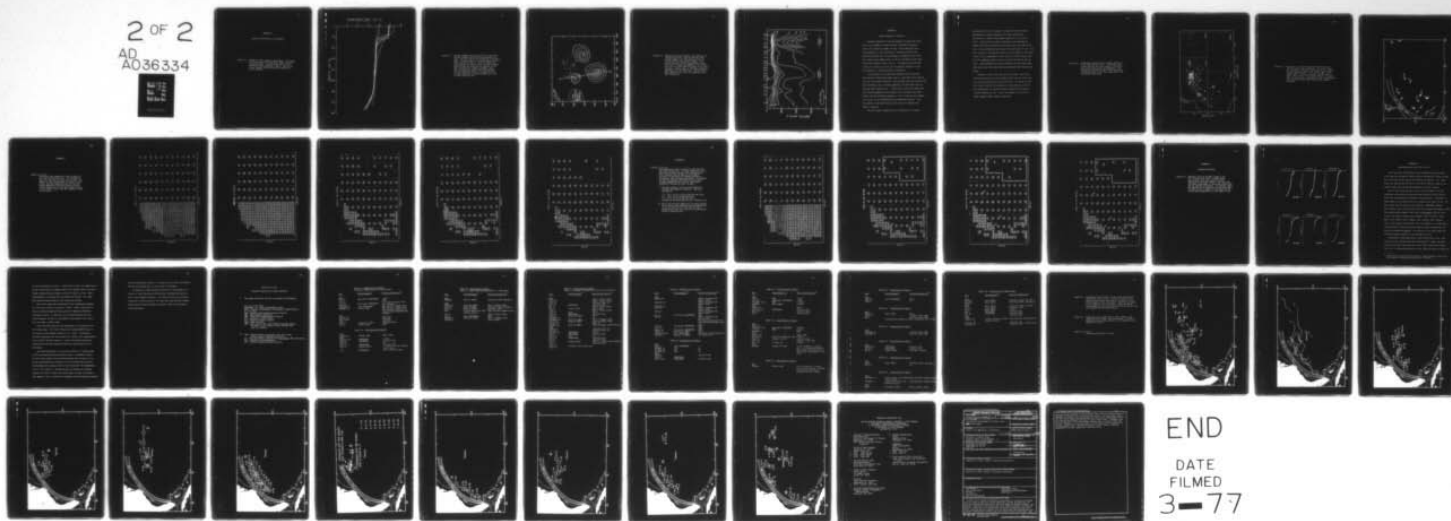
APPENDIX C

Detailed Observations of Warm Eddies

Figure C-1. Examples of XBT's taken in warm eddies. The traces
are reconstructed from digitized values indicated
by small crosses. Typical traces show a thick
isothermal layer extending to 600 m. Some of the
traces ended at 450 m and the main thermocline
was not reached.

TEMPERATURE IN C.

DEPTH IN M.
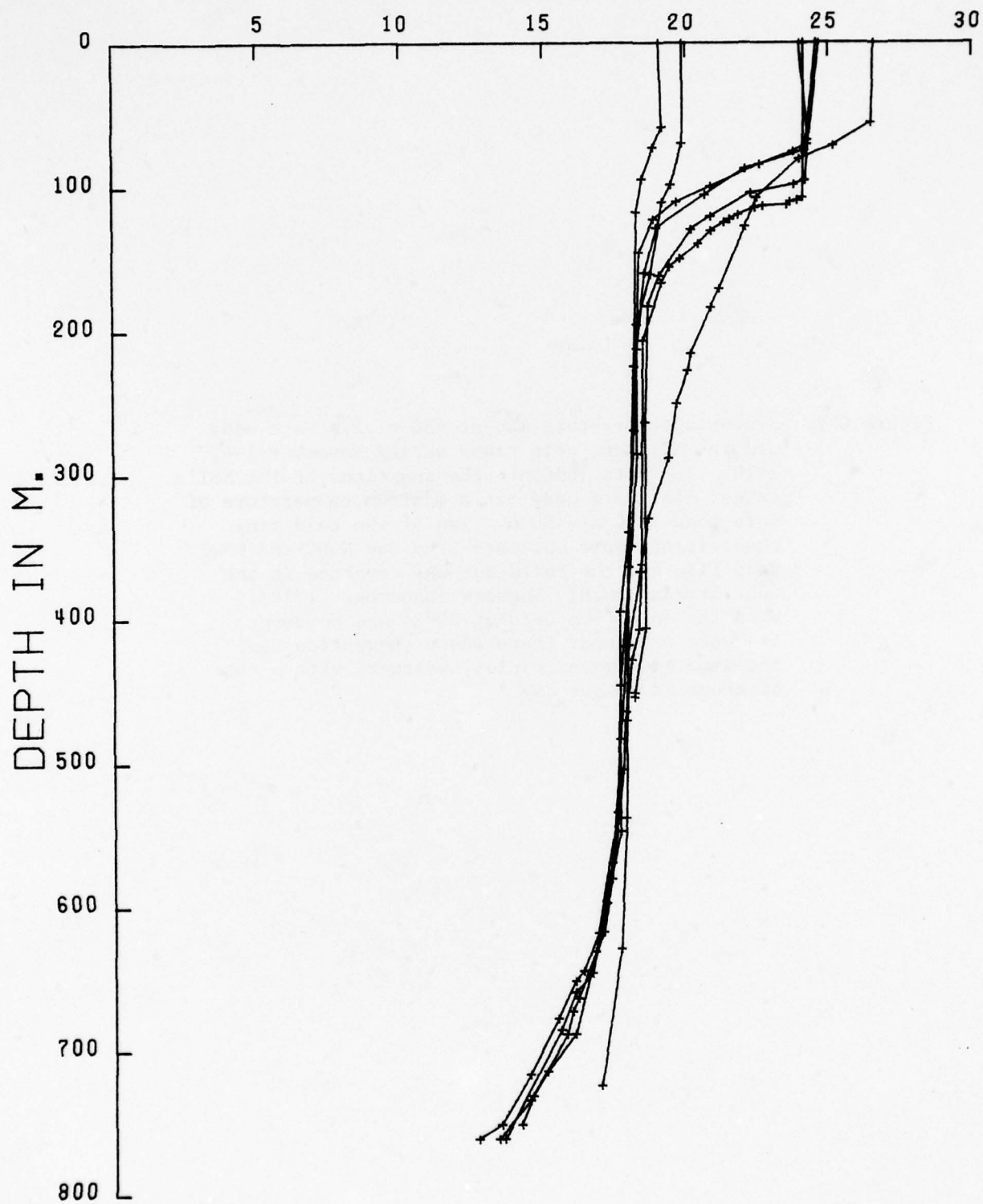
Figure C-2. Synoptic temperature map at 450 m of a warm eddy
and the adjacent cold rings during November 1-4,
1970. The dots indicate the positions of the XBT's
taken. The warm eddy has a maximum temperature of
more than 18°C at 450 m. Two of the cold ring
observations were obtained from the NODC and FNWC
data file and the third one was reported in the
Gulf Stream Monthly Summary (December, 1970).
When the data from October 20-24 and November
1-4 were combined, there was a suggestion that
the warm eddy moved rapidly westward with a rate
of about 20 km per day.
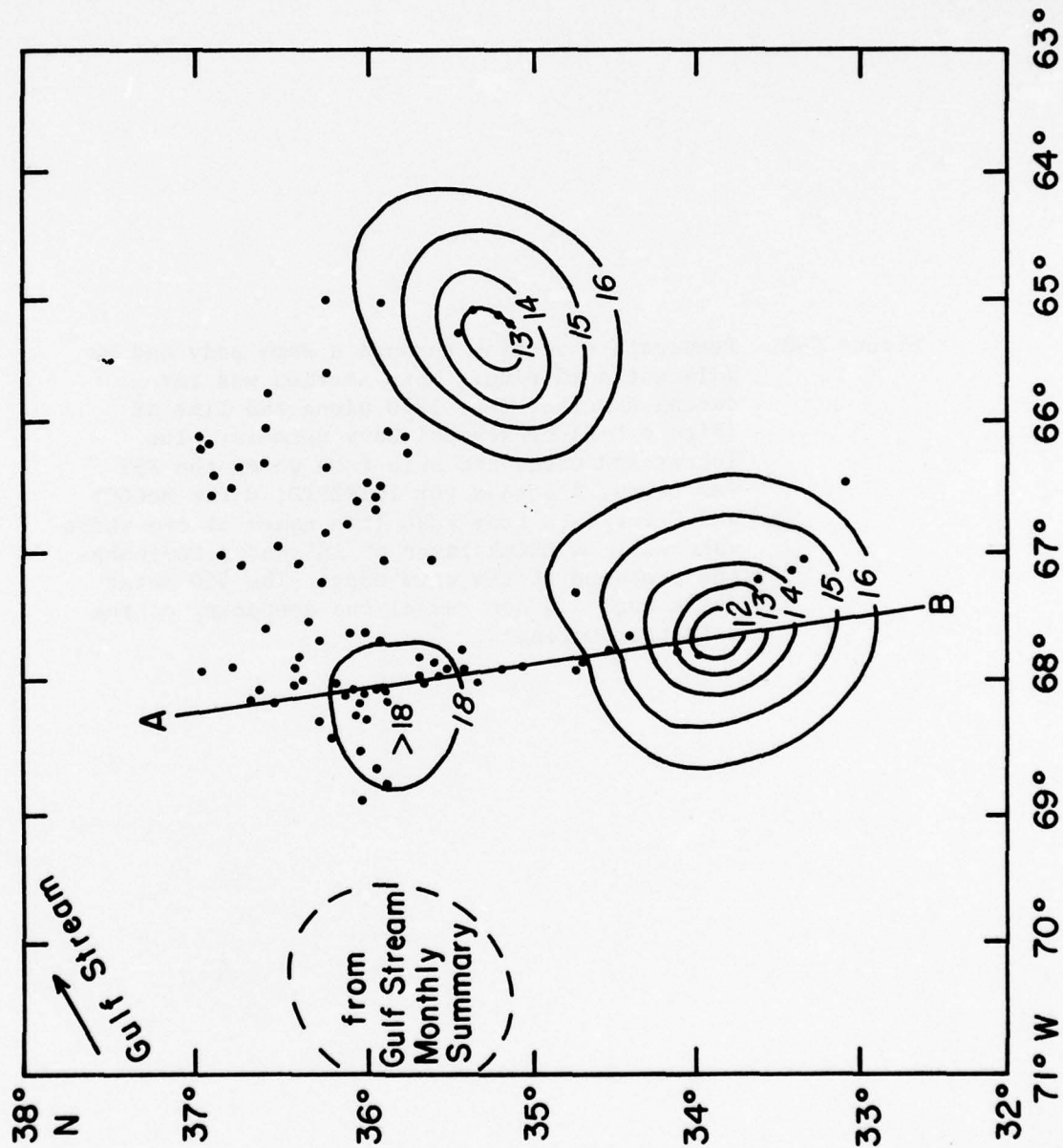
Figure C-3. Temperature section through a warm eddy and an
adjacent cold ring. This section was taken
during November 1-4, 1970 along the line AB
(Figure C-2) by several Navy vessels. The
letter indicates the ship from which the XBT
was taken; A stands for INTREPID, B for McCLOY
and C for data from FNWC (the names of the ships
unknown). A thick layer of 18° Water indicates
the presence of the warm eddy. The 450 meter
XBT's used did not reveal the deepening of the
main thermocline.
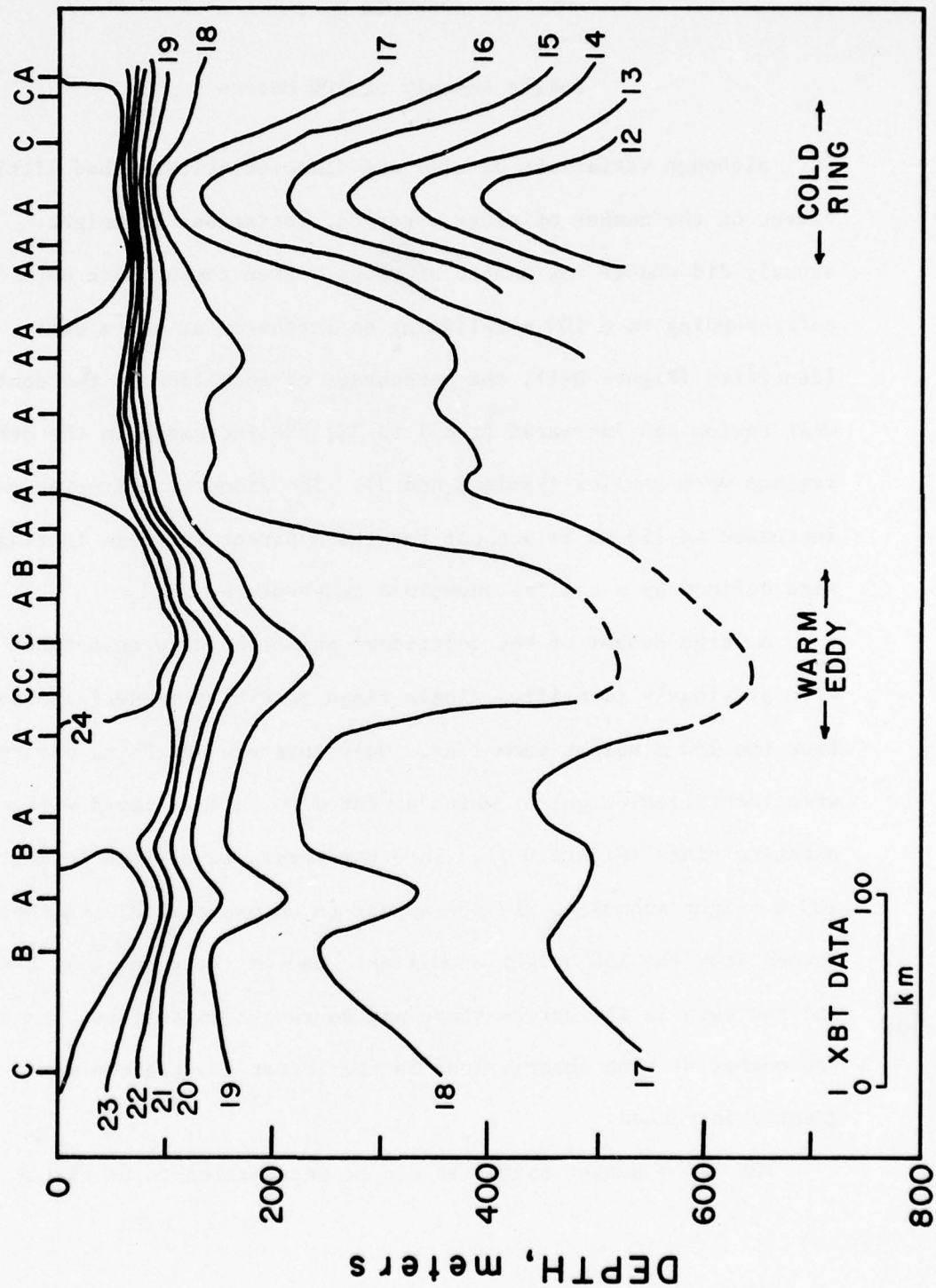
APPENDIX D

Height Anomaly of 100 Meters

Although variations of time and diameter criteria had little effect on the number of rings observed, variations in height anomaly did change the number of rings. When temperature data corresponding to a 100 m uplifting of isotherms at 450 m were identified (Figure D-1), the percentage of anomalies in the southwest region was increased from 1 to 3%; the increases in the other regions were smaller (Table 2 and 3). The diameter criterion was increased to 150 km to account for the apparent increase in ring size defined by a smaller anomalous temperature.

A large number of the additional anomalies were associated with previously identified single rings or ring time-series obtained from the 150 m height anomalies. Only thirteen new "ring observations" were identified, eight of which appeared to be associated with the existing rings (Figure D-2). In other words, five rings formed from 100 m height anomalies did not appear to be associated with those formed from the 150 height anomalies. One of these was near Bermuda, and two each in the northeastern and southwestern regions. Thus, the number of ring observations in the latter two regions were greatly increased.

The 100 m height anomalies can be interpreted to be either

measurements close to the edges of strong Gulf Stream rings or measurements of weaker phenomena (old rings, MODE eddies) consisting of a smaller displacement amplitude of the order of 100 m. Since most of the 100 m anomalies in the northwestern Sargasso Sea were associated with existing rings, the same may be true in the northeastern region where the data density is low. However, because of the high data density and low number of ring observations in the southwestern region, there is the possibility that the 100 m anomalies observed there were mid-ocean eddies and not rings. These anomalies may also be remnants of Gulf Stream rings which moved into this region and whose amplitude have decreased in height.

Attempts to infer ring time-series from these single 100 m "ring observations" and other anomalies which did not satisfy the ring criteria were made but proved fruitless. The series formed were either too short (involving only a few anomalies) to be of much significance, or involved numerous subjective decisions as to which anomalies to use. Thus, the movement of these 100 m height anomaly "rings" remains unresolved.

Figure D-1. Geographical distribution of height anomalies
of at least 100 m at 450 m. The broken lines
divide the area into four regions, according to
the distribution of data and anomalies. The
percentage of anomalies and the 90% confidence
limits are shown at the lower right-hand corner
in each box (see text).

LATITUDE

35

30

25

75   70   65   60   55

LONGITUDE

7·9±1·3

5·6±2·0

11·7±0·5

3·2±0·4
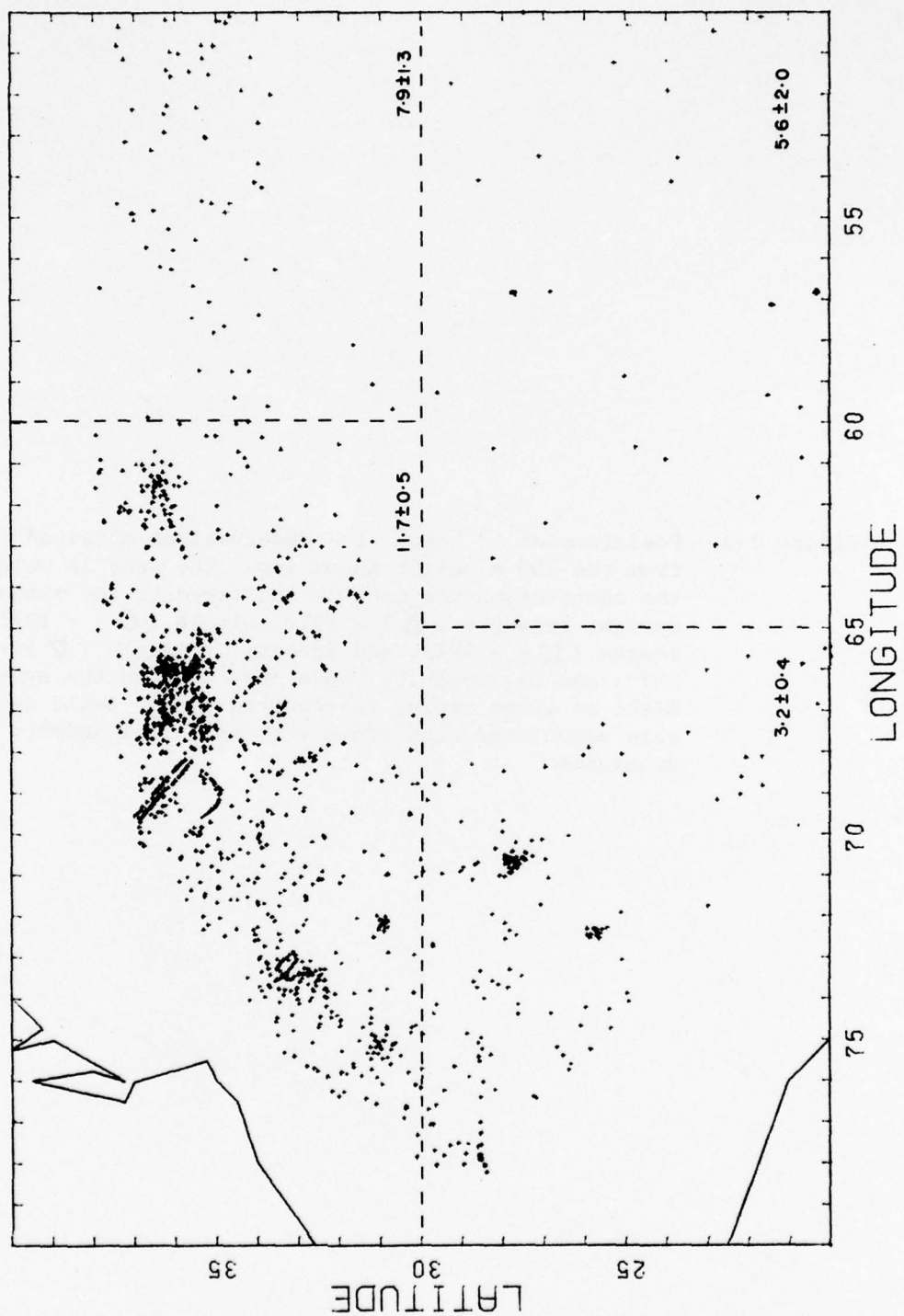
Figure D-2. Positions of 13 "new" ring observations obtained
from the 100 m height anomalies. The year in which
the observation was made is indicated by the symbol:
upright triangle (△) - 1970, circle (O) - 1971,
square (□) - 1972, and inverted triangle (▽) -
1973, and the month by the number next to the symbol.
Eight of these rings, represented by the solid symbols,
were associated with rings from the 150 m height
anomalies.
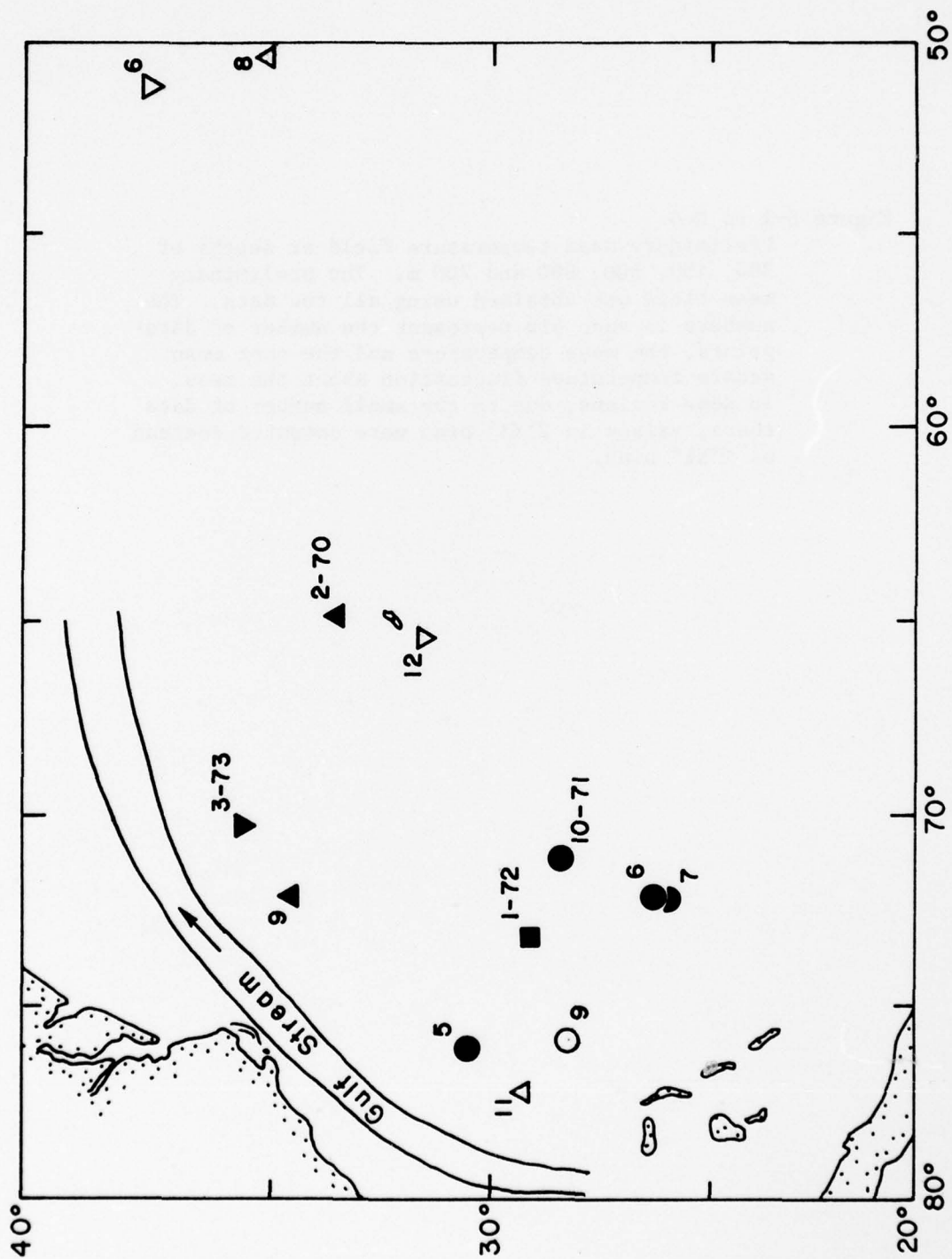
APPENDIX E

Figure E-1 to E-5.
        Preliminary mean temperature field at depths of
        300, 450, 500, 600 and 700 m. The preliminary
        mean field was obtained using all the data. The
        numbers in each bin represent the number of data
        points, the mean temperature and the root mean
        square temperature fluctuation about the mean.
        In some regions, due to the small number of data
        there, values in 2°X3° bins were computed instead
        of 1°X1° bins.

DATA AT 300 METERS

LONGITUDE

LATITUDE

DATA AT 450 METERS

LONGITUDE

LATITUDE

DATA AT 500 METERS

LONGITUDE

LATITUDE

81 80 79 78 77 76 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50

20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

DATA AT 600 METERS

LATITUDE

LONGITUDE

81 80 79 78 77 76 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50

20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

DATA AT 700 METERS

LONGITUDE

81 80 79 78 77 76 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50

LATITUDE
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

APPENDIX F

Figure F-1 to F-4.
        Mean temperature field at depths of 300, 500, 600
and 700 m respectively. The mean temperature field
was obtained using the data after removing those
which deviated from the mean by one standard
deviation in bins where the standard deviation
was greater than one degree Centigrade. The numbers
in each bin represent the number of data points,
the mean temperature and the root mean square
temperature fluctuation about the mean.

  * The mean fields in these bins were biased by
the high percentage of ring data. They were
replaced by:

    * 1 - 16.7, 15.3, 13.5°C at 500, 600 and 700 m,
    * 2 - 14.8, 12.6°C at 600 and 700 m,
    * 3 - 14.5, 12.7°C at 600 and 700 m,
    obtained by interpolating values in adjacent bins.

  ** Due to the low data density in the region bounded
by the thick lines, temperatures were replaced by
14.5, 13.0 and 11.0°C at 500, 600 and 700 m
respectively; they were obtained by interpolating
values in adjacent bins.

DATA AT 300 METERS

LATITUDE

LONGITUDE

DATA AT 500 METERS

LONGITUDE

LATITUDE

DATA AT 600 METERS

LONGITUDE

LATITUDE

DATA AT 700 METERS

LONGITUDE

LATITUDE

APPENDIX G

Seasonal Variations

Figure G-1. Bimonthly plots of the XBT's taken in the
1°X 1° bin of 29°N, 69°W. The XBT traces
were reconstructed from digitized values
indicated by the small crosses. The plots show
the annual development of the surface mixed layer
and the seasonal thermocline. No seasonal signal
was observed in the temperature field below 400 m.
If there is such a signal, it was masked by the
"noise" whose amplitude is on the order of 50 m.

TEMPERATURE IN C.   TEMPERATURE IN C.   TEMPERATURE IN C.

JAN-FEB   MAR-APR   MAY-JUN

JUL-AUG   SEP-OCT   NOV-DEC
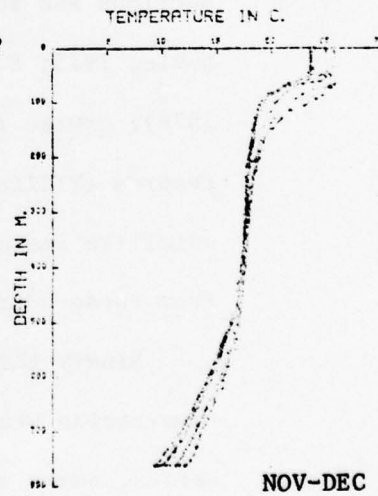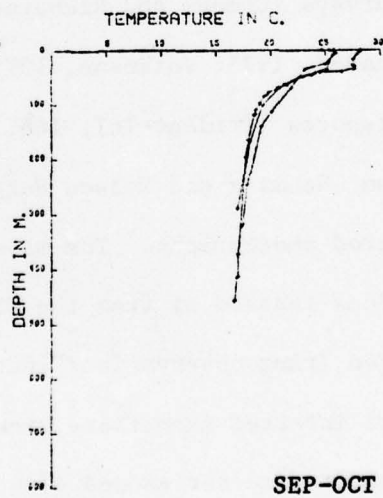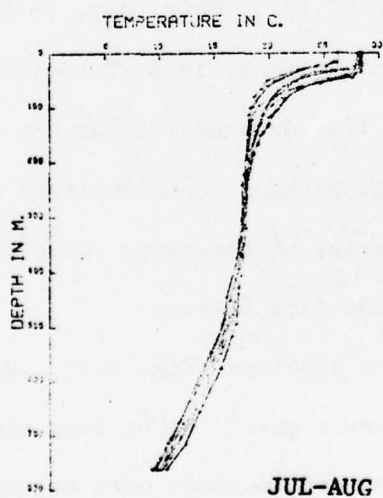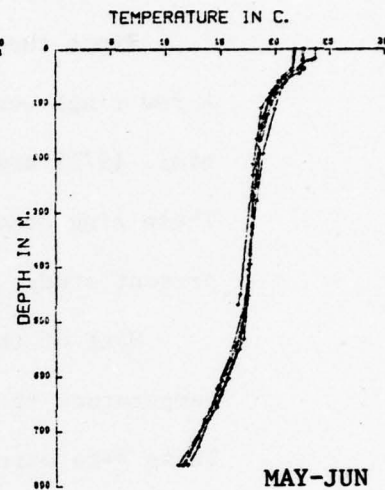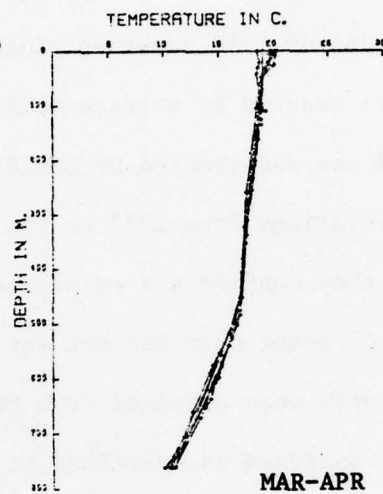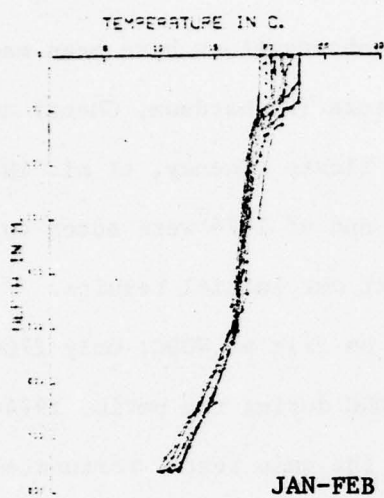
APPENDIX H

Ring Observations from 1974 to 1975

Since the end of 1973 numerous ring observations have been made. A few rings were tracked by surface drifters (Richardson, Cheney and Mantini, 1977) and one was tracked by SOFAR floats (Cheney, et al. 1976). These ring observations from 1973 to the end of 1976 were added to the present study; they confirm and supplement our initial results.

Most of the recent data are not yet on file at NODC; only 1700 temperature records were obtained from NODC during the period 1974-76. These data were analysed as described in the main text. Fortunately a large number of ring observations were obtained from other sources. The main sources that we used were the following: NAVOCEANO technical notes (Cheney, 1976; Gotthardt and Doblar 1974; Cheney and Khadouri, 1975); Gulf Stream Monthly Summary (1974) and the Gulfstream (1975-76); XBT sections and surveys (Cheney and Richardson, 1975; McCartney, 1975a; Noble, 1975; Seaver, 1975; Volkmann, 1975; Leetmaa, 1976; Vukovich, 1976), cruise reports (Trident-161, 168, 175; Oceanus-7), current meter records (William Schmitz and Nelson Hogg, personal communcation) and satellite infrared photographs. The majority of the rings found came from these sources instead of from the NODC data file.

Ninety-three "ring observations" were obtained (Fig. H-1). Ring time-series were inferred from these observations.[1] Eight long time-series, seven short time-series and eleven single rings were obtained (Fig. H-2). Detailed observations of these rings are shown in Tables H-1

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[1] During 1974-76 there are practically no single anomalies, which were very useful in establishing time-series in 1970-73.

to H-16 and figures H-3 to H-11. During 1974 to 1976, six rings were ob-
served to move along the familiar path on the offshore side of the Gulf
Stream, constituting an average of about two rings in a year. These
rings appeared to coalesce with the Stream near Florida. Two rings
were actually found attached to the Stream near Florida.

Most of the rings were concentrated in the northwestern Sargasso
Sea, but eight rings were found east of 60°W. Some of them were the
large Gulf Stream Extension Rings reported by McCartney (1975a) and
Worthington (1976). At least one of these moved westward into the
western Sargasso Sea and its twelve-month track appears to be consis-
tent with those of other rings.

Since 1974 there have been two experiments to continuously track
Gulf Stream rings. The first consisted of launching SOFAR floats in
two rings at various depths (Cheney, et al., 1976). One ring was
followed continuously for three months as it moved to the westnorthwest
with a speed of 6cm/sec (ring A). A second ring seeded with floats
coalesced with the Gulf Stream near 60°W only three months after it
had formed.

The second experiment to track rings consists of a program using
satellite-tracked free-drifting surface buoys. Preliminary results
in three rings indicate that one moved westward for one month, one is
moving southwestward just offshore of the Gulf Stream and one moved
northeastward and coalesced with the Gulf Stream near 55°W (Richardson
et al., 1977) (ring I). Although we need to continue the tracking
program to be able to reveal the typical paths of rings, two results
have emerged. One is a qualitative agreement with the analysis presented

here from temperature records. The second is that rings can coalesce with the Gulf Stream after a life of only a few months.

In general the ring time-series from 1974 to 1976 appear to be similar to those observed in previous years although they appear to have a more "wriggly" character. We think this is due to the better resolution of the positions of the rings plus their probable looping motion which has been observed by Fuglister (1972) from continuous ring observations.

Table H-1 to H-16

Detailed Observation of Rings (1974-76).

*   The agency which runs the ship is enclosed in parenthesis.

        CG – U.S. Coast Guard
        NAVOCEANO – U.S. Naval Oceanographic Office
        NOAA – National Oceanographic and Atmospheric Administration
        N – U.S. Navy
        NESS – National Environmental Satellite Service
        NRL – Naval Research Laboratory
        WHOI – Woods Hole Oceanographic Institution
        URI – University of Rhode Island
        RTI – Research Triangle Institute
        DUKE – Duke University
        FNWC – Data from the Navy Fleet Numerical Weather Central
               The names of the vessels in which the data were
               taken are unknown.

**   GSMS – Ring Observations reported in the Gulf Stream
              Monthly Summary, NAVOCEANO publication
       GS – Ring observations reported in the Gulfstream, NOAA publication.
       XBT – expendable bathythermography
       STD – salinity-temperature-depth stations.

TABLE H-1. <u>Observations of Ring A.</u>
(tracked by SOFAR floats for three months)

<u>Date</u>	<u>Platform/Agency</u>[*]	<u>Observations/Sources</u>[**]
1974		
June 17	Sea Venture (NAVOCEANO)	5 XBT's
July 14		GSMS
July 30		In several transects from
August 30	Sea Venture (NAVOCEANO)	NY to Bermuda.
September 30	Lynch (NAVOCEANO)	XBT, STD and 3 SOFAR floats
December 10	Trident (URI)	XBT, STD and 2 SOFAR floats
		The ring was tracked by two
		floats between September and
		December.
1975		
February 10		Navy Ship
March 23-26		satellite
April 7		satellite
April 9	Advanced II (RTI)	Vukovich (1976)
June 1	Trident (URI)	XBT's

TABLE H-2. <u>Observations of Ring B.</u>

1975		
December 8	Trident (URI)	XBT's, STD's
1976		
February 18	(NAVOCEANO)	4 XBT's
March 8	(NAVOCEANO)	satellite data
March 27		GS
April 14	(NAVOCEANO)	satellite data
June 12	Oceanus (WHOI)	A surface buoy was launched
		in the ring.
July	(NAVOCEANO)	XBT's, satellite data

TABLE H-3. Observations of Ring C.
(This is a Gulf Stream Extension Ring or a "Big Baby").

Date	Platform/Agency[*]	Observations/Sources[**]
1974		
November	Knorr-43 (WHOI)	McCartney (1975) Big Baby 3
1975		
January 24	Chain-118 (WHOI)	XBT's Volkmann (1975)
March 25	Knorr-48 (WHOI)	McCartney (1975) Big Baby 5
April 6	Knorr-49 (WHOI)	McCartney (1975)
May 1	current meters with temperature records.	Hogg (personal communication)
June 17		AXBT's, Cheney (1976)
July 5	Lynch (NAVOCEANO)	XBT's
September	Chain-127 (WHOI)	XBT's. Volkmann (1975)
October 14		Cheney (1976)

TABLE H-4. Observations of Ring D.
(This is the Ring D referred to by some ring scientists).

Date	Platform/Agency[*]	Observations/Sources[**]
1975		
March 24		AXBT's, Cheney (1976)
April 14		AXBT's, Cheney (1976)
April 24		satellite data, GS
May 12	(NOAA/NESS)	satellite data
May 21		AXBT's, Cheney (1976)
June 7	Trident (URI)	XBT's, STD's
June 17		AXBT's, Cheney (1976)
June 25	Lynch	XBT's
July 28	(NAVOCEANO)	satellite data
August 8	Chain-125 (WHOI)	XBT's
September 2		GS
September 30	Chain-127 (WHOI)	XBT's, Volkmann (1975)
October 14	Eastward (DUKE)	Hogg and Dunlap (1976)
October 29		AXBT, GS
November 20	Knorr-53 (WHOI)	Wiebe (personal communication)
1976		
January 6		satellite data, GS
February 5		satellite data, GS
February 18	(NAVOCEANO)	AXBT's
March 1	(NOAA/NESS)	satellite data
March 31	(CG)	GS
April 14	(NAVOCEANO)	satellite data
May 20		satellite data
June 6	Oceanus (WHOI)	XBT's, a surface buoy launched
June 13		satellite data
July 14		
August 14	tracked by the surface buoy	

TABLE H-5. <u>Observations of Ring E.</u>

<u>Date</u>	<u>Platform/Agency</u>[*]	<u>Observations/Sources</u>[**]
<u>1974</u>		
January 28		AXBT's, Gotthardt and Doblar (1976)
February 2-5		AXBT's, Gotthardt and Doblar (1976)
February 27		GSMS
April 16		AXBT's, Gotthardt and Doblar (1976)
April 27		AXBT's, Gotthardt and Doblar (1976)
May 30	Sea Venture (NAVOCEANO)	XBT
June 14		AXBT's, Gotthardt and Doblar (1974) The ring coalesced with the Gulf Stream and formed a new ring.
June 30	Sea Venture (NAVOCEANO)	XBT's
July 19		GSMS
August 16	Sea Venture (NAVOCEANO)	XBT's
August 19	Atlantis II (WHOI)	XBT's
September 24-27	Lynch (NAVOCEANO)	coalescence with Stream with
October 6	Atlantis II (WHOI)	six floats in it.

TABLE H-6. <u>Observations of Ring F.</u>

<u>1975</u>		
July 2	Lynch (NAVOCEANO)	
November 2	(CG)	GS
November 20	(CG)	GS
December 26	(CG)	GS
<u>1976</u>		
February		satellite data
March 31	(NAVOCEANO)	
April 11-14	(NOAA/NESS)	satellite data

TABLE H-7. Observations of Ring G.

Date	Platform/Agency[*]	Observations/Sources[**]
1973		
June 7	FNWC	1 XBT
July 20	Ambassador (NAVOCEANO)	6 XBT's
September 8,11	FNWC	13 XBT's
December	Knorr (WHOI)	10 XBT's
1974		
January 29		AXBT's
April 12, 16	(NOAA/NESS)	satellite data
April 30		satellite data
May 5		satellite data

TABLE H-8. Observations of Ring H.

1973		
August 31		
September 9,14	Ambassador (NAVOCEANO)	30 XBT's
October 7	FNWC	2 XBT's
November 27		GSMS
1974		
January 26		AXBT's, GSMS
February 21	Fiske (N), Marshfield (N)	2 XBT's
March 25	Advance II (RTI)	Vukovich (1976)
March 30		satellite data, GSMS
April 20	J. Hewes (N)	3 XBT's
1975		
November	Trident-175 (URI)	It was tracked by a surface buoy. It moved northeastward and finally coalesced with the Gulf Stream. (Richardson et al. 1976).

TABLE H-9. Observations of Ring I.

1975		
November	Trident (URI)	It was tracked by a surface buoy for four months. It moved northwestward and finally coalesced with the Stream.

TABLE H-10. Observations of Ring J.

Date	Platform/Agency[*]	Observations/Sources[**]
1975		
June 28	Lynch (NAVOCEANO)	XBT's
August 4		GS

TABLE H-11. Observations of Ring K.

Date	Platform/Agency	Observations/Sources
1974		
March 26	Knorr (WHOI)	XBT's
April 17		satellite data, GSMS
May 1		satellite data, GSMS
northwestward movement possible coalescence with Stream.		

TABLE H-12. Observations of Ring L.

Date	Platform/Agency	Observations/Sources
1974		
September 11		satellite data, GSMS
September 27		satellite data, GSMS

TABLE H-13. Observations of Ring M.

Date	Platform/Agency	Observations/Sources
1975		
February 13	(NOAA/NESS)	satellite data
March 23	(NOAA/NESS)	satellite data
May 25	Trident (URI)	attached to Stream

TABLE H-14. Observations of Ring N.

Date	Platform/Agency	Observations/Sources
1975		
March	Knorr (WHOI)	McCartney (1975, Big Baby 6
May 3-9		GS

TABLE H-15. Observations of Ring P.

Date	Platform/Agency	Observations/Sources
1975		
September 15	current meters with temper-ature records	Hogg (personal communication)
November 5	current meters with tem-perature records	Hogg (personal communication)
1976		
April	Researcher (NOAA)	XBT's, Leetmaa (1976)

TABLE H-16. Observations of Single Rings.

Date	Platform/Agency[*]	Observations/Sources[**]
1974		
November	Knorr (WHOI)	McCartney (1975), Big Baby 1
November	Knorr (WHOI)	McCartney (1975), Big Baby 2
1975		
March	Knorr (WHOI)	McCartney (1975), Big Baby 4
March 4	Knorr (WHOI)	McCartney (1975)
April 4	Knorr (WHOI)	5 XBT's
May 5	(NAVOCEANO)	satellite data
May 10	(NAVOCEANO)	satellite data
June		satellite data
1976		
January 20	current meters with temperature records	Hogg (personal communication)
February 28		satellite data
February 28		satellite data a double ring

Figure H-1. Geographical distribution of the 93 ring observations
made during 1974 to 1976. The year in which the ob-
servation was made is indicated by the symbol: circle –
1974, triangle – 1975, and square – 1976, and the month
by the number next to the symbol. There are eleven
single rings not associated with any time-series and they
are indicated by the solid symbols.

Figure H-2. Ring time-series during 1974 to 1976. Broken lines
represent a gap of more than three months. Detailed
observations are shown in Table H-1 to Table H-15 and
Figure H-3 to H-11.

Figure H-3 to H-11.
Detailed observations of rings.

GULF STREAM

BERMUDA

200 m

40

30

20

50

60

70

80

BERMUDA

A

6-74

7-74

8-74

9-74

10-74

SOFAR FLOATS

12-74

2-75

6-75

3-75

4-75

GULF STREAM

200m

C

GULF STREAM

200m

BERMUDA

11-74
1-75
3-75
4-75
6-75
5-75
9-75
10-75

coalesced with the stream and formed a new ring

coalesced with the stream with 6 floats in it

coalesced with the stream

BERMUDA

GULF STREAM

200m

A 1–74
B 2–74
C 4–74
D 5–74
E 6–74
F 6–74
G 7–74
H 8–74
I 9–74

F E D C B A E G H I

40 30 20 50 60 70 80

BERMUDA

GULF STREAM

F

7-75

?

11-75
11-75

12-75

2-76

3-76

4-76

200m

50   40   30   20

80   70   60

G

6-73

7-73

12-73

1-74

4-74

5-74

9-73

BERMUDA

GULF STREAM

200 m

40

30

20

50

60

70

80

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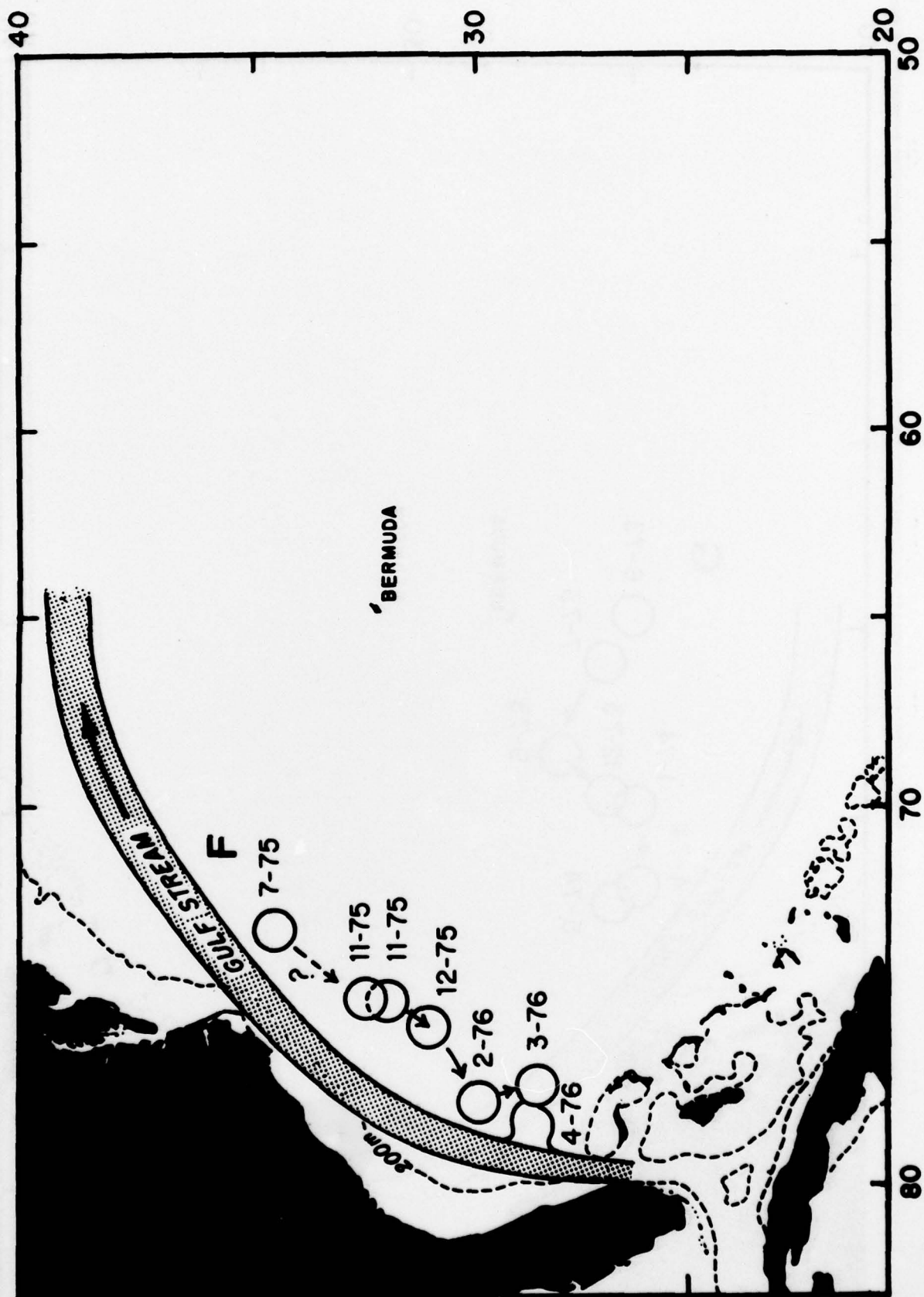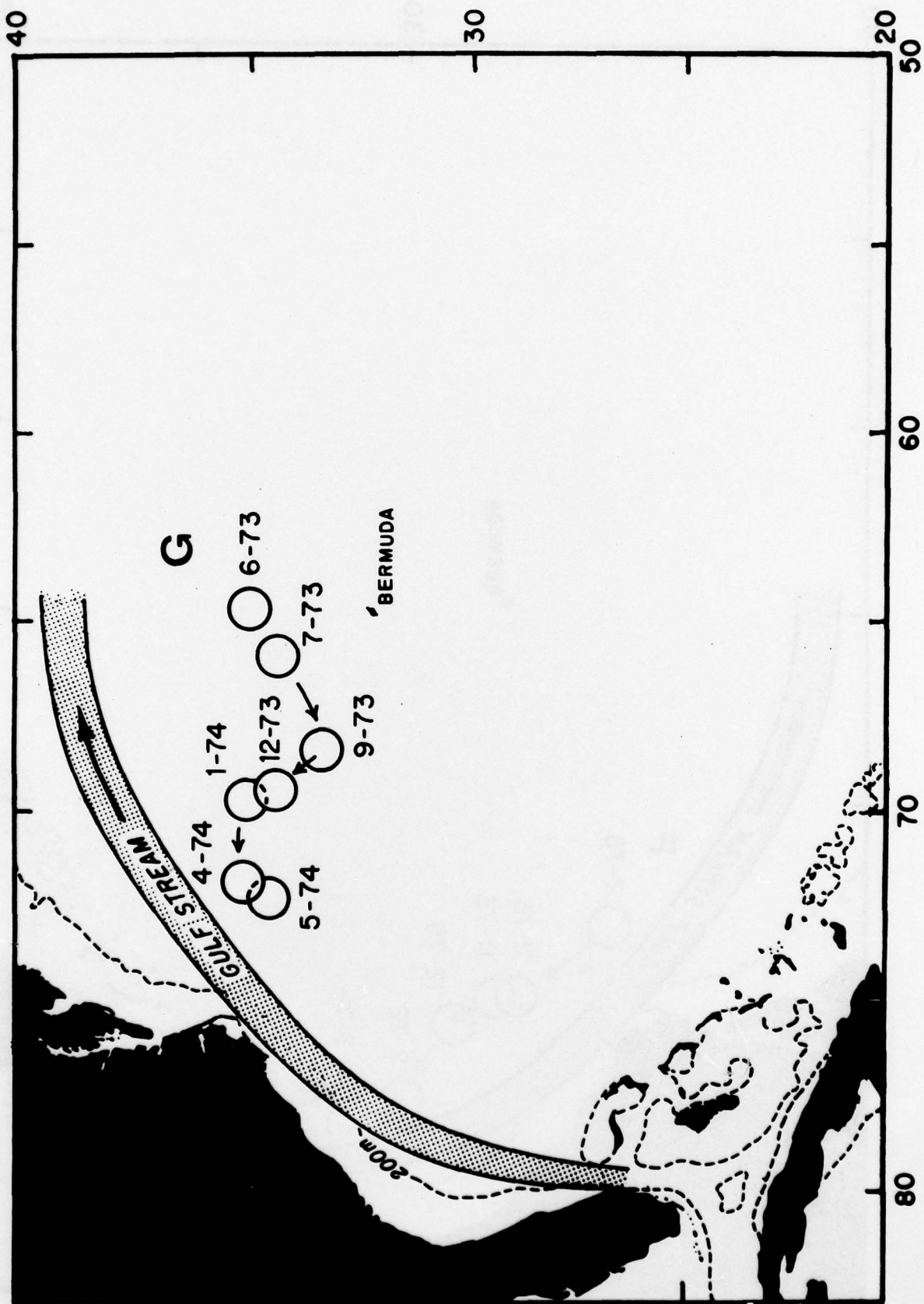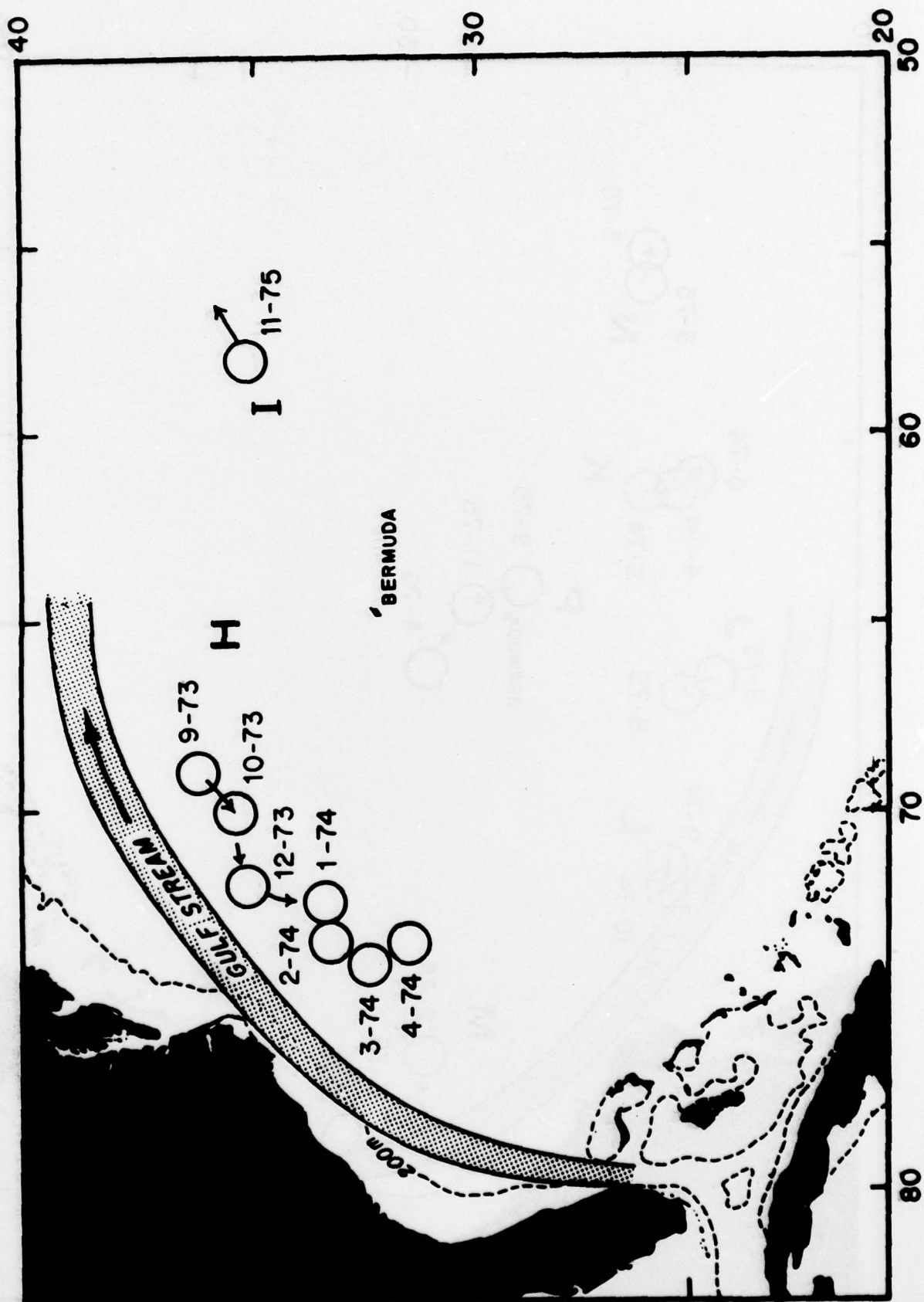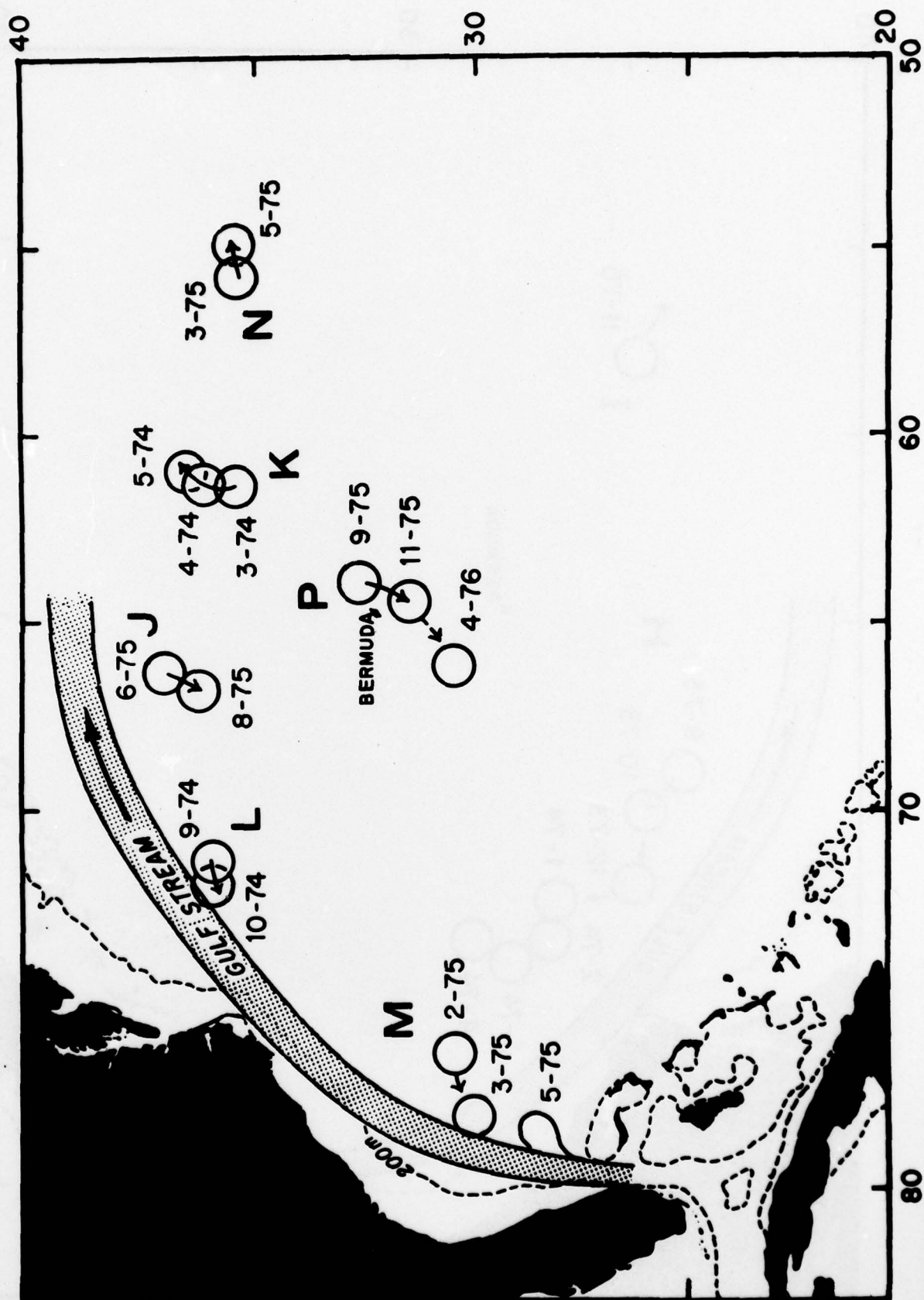   Arlington, VA 22217
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A study of the general distribution and movement of cyclonic Gulf Stream rings was made by analysing 50,000 temperature records obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central. The data were taken from 1970 through 1973 in the region bounded by 20-40°N and 50-80°W. Additional ring observations from other sources were also used. Twelve ring time-series, together with fifteen single ring observations were obtained; approximately eleven rings were found to exist at one time. They

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typically moved westward, turned southwest when close to the Gulf Stream and appeared to coalesce with the Stream near Florida. On the average, about one and a half rings a year moved down this path, with a mean speed of three km a day and an estimated life span of two to three years. Although rings were concentrated in the northwestern Sargasso Sea, a few were found east of 60°W. However, the low data density in the eastern region prevented detailed analysis there. Several warm eddies, with at least a 150-meter deepening of the main thermocline, were also found.